# Toward 100 GHz direct modulation rate of antenna coupled nanoLED

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**Abstract:** We show that > 100 GHz direct modulation rate while maintaining a quantum efficiency higher than 25% is possible by using an optical antenna to enhance the spontaneous emission rate of an electrically injected III-V nanoLED.

## I. Introduction

Because of long spontaneous emission lifetime (~1 ns), traditional semiconductor light emitting diodes (LEDs) have low direct modulation rates (< 1 GHz) and limited application for optical communication. By coupling the active region of a nanoscale semiconductor LED (nanoLED) to an optical antenna, it is possible to dramatically increase the spontaneous emission rate by several orders of magnitude allowing for direct modulation rates exceeding 100 GHz [1,2]. The nanoLED could have application as a small, fast, and efficient light source for on-chip optical interconnects. There have been many demonstrations of spontaneous emission rate enhancement of optically pumped materials coupled to an optical antenna; however, practical implementation of an antenna-coupled device requires an electrical injection scheme. Electrical injection must be implemented in a manner that does not perturb the antenna mode while minimizing the parasitic RC time constant and carrier transport time into the active region. Existing demonstrations of electrically injected antenna-coupled devices include a GaAs-based LED coupled to a strip antenna [3], and several reports of using an antenna to influence the light emission from a metal-insulator-metal (MIM) tunnel junction [4-6]; although spontaneous emission rate enhancement or efficiency have so far been low using these approaches. We recently experimentally demonstrated large spontaneous emission rate enhancement from an electrically injected nanoLED consisting of a III-V semiconductor ridge inserted into the feedgap of a cavity-backed optical slot antenna [7]. This approach is novel in that the antenna serves as an electrical contact thereby allowing for localized electron injection without perturbing the antenna mode and furthermore the active region is completely self-aligned to the antenna negating the need for precise lithographical alignment. In this study, we analyze the theoretical direct modulation rate and efficiency of an optimized nanoLED based on this device architecture. We find that direct modulation rates exceeding 100 GHz is possible through optimization of the optical antenna design and active region.

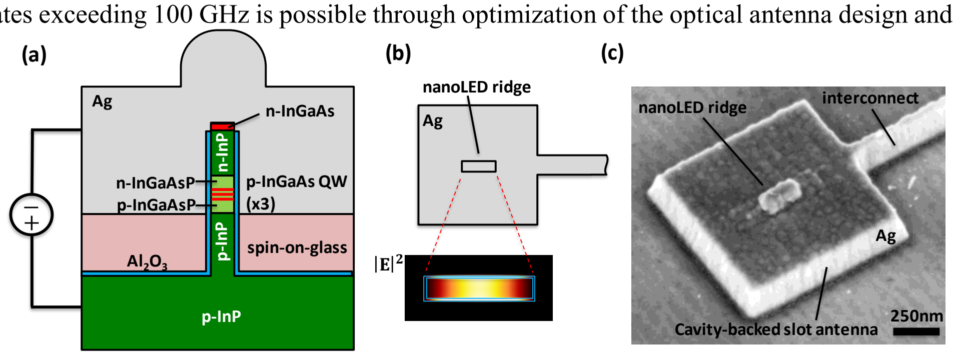


**Figure 1.** (a) Cross-section schematic of electrically injected InP/InGaAs nanoLED ridge coupled to cavity backed slot antenna; (b) Top-view of nanoLED showing electromagnetic energy density within the slot; (c) SEM image of fabricated nanoLED

## II. Electrically injected nanoLED design

The nanoLED consists of a nanoscale InP/InGaAs multiple quantum well (MQW) pn junction ridge with conformal covering of silver (Ag) metal (Figure 1). This geometry naturally forms a cavity-backed optical slot antenna in which the antenna resonance frequency is defined by the ridge dimensions. Shown in Figure 1b is a top-view of the simulated electromagnetic energy density of the antenna mode indicating the presence of high spontaneous emission enhancement within the slot and active region. According to simulation, spontaneous emission rate enhancement greater than 1000-fold is achieved by scaling the ridge width below 20nm. Electrons are electrically injected into the MQW active region via the electrically-contacted antenna and holes are injected through the p-type InP substrate. Contact resistance is minimized by using a highly doped InGaAs n-contact layer and a thick spin-on-glass layer offsets the antenna from the p-type substrate to reduce parasitic capacitance. Given the radiative rate is proportional to the product of the hole and electron density ($R_{rad} \cong Bnp$) we choose to heavily p-type dope ($p_0 = 5 \times 10^{19}$ cm$^{-3}$) the active region to ensure high radiative rate at low current density. The InGaAsP cladding regions will also be doped to minimize carrier diffusion time into the active region which would otherwise limit the direct modulation rate. Doping is known to decrease efficiency through non-radiative recombination and free carrier absorption but has limited effect in the nanoLED due to the competing high spontaneous emission rate and low-Q of the antenna mode [8].

## III. Direct modulation rate and efficiency

Using a rate equation approach and rigorously solving for the spontaneous emission rate under the parabolic band approximation we have calculated the 3-dB frequency ($f_{3dB}$) and quantum efficiency of the directly modulated nanoLED. Antenna metal loss, surface recombination, Auger recombination, carrier overflow, and contact resistance have been included in our model as the dominant sources of loss. Shown in Figure 2a and 2b is $f_{3dB}$ and efficiency plotted as a function of current density for a nanoLED with a ridge width of 10 and 20 nm. Remarkably, an $f_{3dB}$ of 115 GHz with an efficiency of ~25% is predicted with the 10nm wide device. Higher efficiency of ~40% can be achieved by increasing the ridge width to 20 nm with a reduction of $f_{3dB}$ to 55 GHz. The efficiency at low current density is limited mostly by loss in the antenna metal. Despite the large surface-to-volume ratio, surface recombination does not significantly affect the efficiency due to the large competing spontaneous emission rate. For the same reason, the nanoLED supports significantly higher current density than a traditional LED. At very high current density, the efficiency drops from increased Auger recombination, contact resistance loss, and carrier leakage into the cladding layers. For comparison, we also show a 10 nm wide ridge without active region doping and without antenna in Figure 2a and 2b. If the active region is undoped, large current drive is needed to reach high speed and efficiency. The nanoLED without antenna has $f_{3dB}$ of 3 GHz at low current drive as a result of large surface recombination but is inefficient without antenna-enhanced spontaneous emission.

We consider the use of the nanoLED as the emitter in an optical link by plotting the energy per bit (of the nanoLED emitter only) as a function of number of photons per bit for 1, 10, 40, and 100 Gbps data rates. In Figure 2c, we plot the data for a single nanoLED with 10 nm wide ridge and assume a 70% coupling efficiency from the nanoLED into the optical waveguide [9]. Although the nanoLED is capable of high direct modulation rates, the output power is less than 1 $\mu$W due to the small active region volume. 100 Gbps operation with ~20 aJ/bit nanoLED emitter energy can be achieved for detector sensitivity near the quantum limit of 20 photons per bit. The detector sensitivity requirement can be relaxed to 1000 photons per bit by operating the nanoLED at a slower data rate of 10 Gbps with ~1 fJ/bit emitter energy. For any optical link, the receiver energy will have opposite trend shown in Figure 2c and therefore the optimum operating point for the optical link will be a balance between emitter and receiver energy.

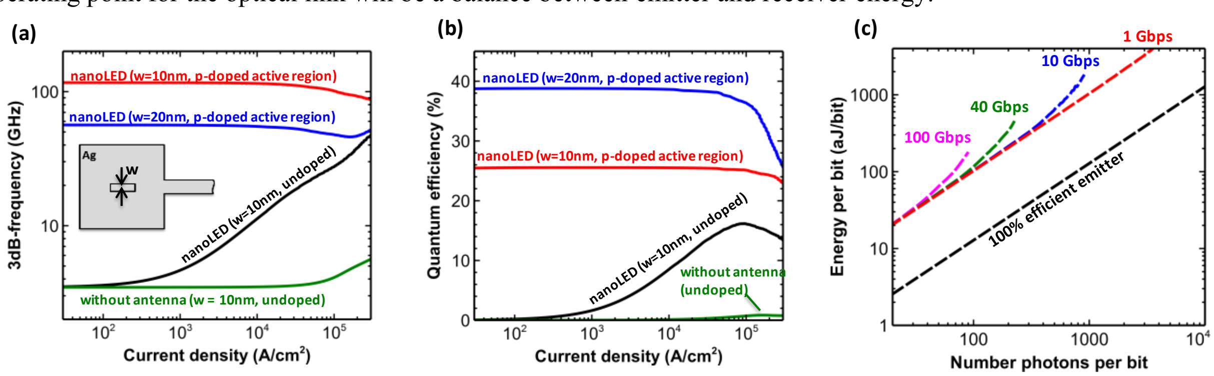


**Figure 2.** (a) Predicted 3dB-frequency ($f_{3dB}$) as a function of current density. Inset shows top-view schematic of nanoLED showing the ridge width dimension; (b) Quantum efficiency plotted as a function of current density; (c) Energy per bit of the nanoLED transmitter only; plotted as a function of number of photons per bit for four different data rates

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