

High-speed nanoLEDs for chip-scale communication

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ABSTRACT

Fast and efficient light generation and transport are at the heart of modern on-chip optical communication and information processing technologies. Next generation on-chip light sources must have a high modulation bandwidth and low energy consumption while maintaining a small footprint to be competitive. Enabled by metal-cladded nanocavities, fast subwavelength light emitters in the form of both lasers and LEDs have been analytically or experimentally demonstrated. From the modulation bandwidth perspective, nanolasers are ultimately limited by gain compression at high injection currents. From the energy efficiency perspective, nanolasers are inefficient due to the required high injection current to compensate for the losses in order to reach the lasing threshold. In contrast, nanoLEDs can simultaneously have Purcell effect enhanced speed, high energy efficiency, and output power that is above the thermal noise limit. This brief review aims to bolster, in a comparative approach, rationales of why nanoLEDs are a competitive alternative to nanolasers as light sources in chip-scale optical communication systems.

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1. Introduction

Cisco's 2020 forecast predicts that two-thirds of the global population will have internet access by 2023, and the number of devices connected to IP networks will be more than three times the global population by then [1]. Given that over 70 percent of IP traffic resides within data centers, there is a continuous need to increase both the energy efficiency and speed of short-range data communication. On the interconnect level, the current data transfer method via copper wires is limited by both bandwidth and energy efficiency, and has become the performance bottleneck in today's microchips used in data centers and other modern communication systems [2]. To overcome these limitations of electrical connections, optical interconnects have been proposed as a solution for both intra-chip and chip-to-chip communication [2–5], and an essential component of an optical interconnect in photonic integrated circuits (ICs) is an on-chip light source.

Lasers have long been established as the light source for long-haul optical fiber communications due to their high output power, small divergence angle, coherent emission, and fast modulation speed. These same reasons make lasers an obvious choice when downscaling light sources for chip-scale circuits. Over the last decade, nanolasers (lasers with sub-wavelength physical and modal volumes) have been frequently proposed as candidates for on-chip light sources [6–9], and tremendous progress has been made. However, as the physical size reduces

towards the sub-wavelength scale, conventional laser designs become increasingly inefficient, mainly due to poor optical confinement. To circumvent this issue, the prospect of using metal in laser cavity designs emerged, exploiting the capability of metals to confine light to deep sub-wavelength dimensions [10,11], and a plethora of metal-clad nanolasers were demonstrated [12–16]. Indeed, metal-clad nanolasers can offer many advantages such as ultra-high integration density and potentially fast modulation speed [6,7,17]. Nonetheless, metal also leads to an exceedingly high lasing threshold by introducing significant joule loss at optical frequencies. As a result, research in this field has focused on demonstrating proof-of-concept optically pumped lasing action, usually at high pump powers to reach the lasing threshold and under ultra-fast pulsed pumping to reduce self-heating [18,19]. So far, only a few works reported electrically pumped lasing action [10,14–16], and continuous-wave operation at room temperature was only achieved in one report at a high threshold current exceeding 1 mA [16].

It is fair to say that these laboratory demonstrations are not suitable for chip-scale integration due to the requirement of external optical pumping or high injection current levels, as well as insufficient output power, low expected coupling efficiency to an on-chip waveguide, and high device impedance of tens of kilo-Ohms [20,21]. In addition to these inherent limitations that lead to a low emitter efficiency, the driver circuitry has not been investigated for nanolasers, thus compromising the wall-plug efficiency (WPE). The poor device and system efficiencies have led to the debate over nanolaser's usefulness [22].

In terms of operation speed, the spontaneous emission rate is one of the factors that determine how fast a light source can

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be modulated. At subwavelength dimensions, cavity quantum electrodynamical effects alter the spontaneous emission rate. An emitter's spontaneous emission rate can be enhanced by the Purcell effect, which describes the spontaneous emission rate modification in a cavity compared to free space [23]. Because the modification factor, termed Purcell factor, scales inversely with the cavity mode volume, nanoscale light sources' spontaneous emission rate can be much faster than that of their large-scale counterpart. To this end, the Purcell effect has been extensively studied in nanolasers. However, due to gain compression effects, nanolasers are not able to reach the expected high modulation bandwidth. Gain compression often encompasses several damping mechanisms such as spatial and spectral hole burning, carrier diffusion, and nonlinear absorption. Regardless of which mechanism dominates, they all contribute to damping, and even a small level of gain compression leads to a dramatic effect in a nanolaser's dynamic response [24].

On the other hand, LEDs are not traditionally considered suitable light sources for high-speed optical communication due to their low modulation speed limited by the slow intrinsic spontaneous emission rate. In the advent of nanoscale LEDs (nanoLEDs), this speed limitation is lifted due to the significant Purcell effect without the penalty of large gain compression as in the case of nanolasers. Because the application of interest is high-speed on-chip communication, small light source footprint, high speed, low power consumption, minimal external circuitry and system structure for easier integration are the most desired features. Based on these criteria, nanoLEDs are a suitable alternative to nanolasers in optical interconnects due to their smaller footprint, higher single-channel speed, lower power consumption, and simpler system structure. In contrast, if wavelength division multiplexing (WDM) is required in future optical interconnects, nanolasers can potentially be superior given that single-channel speed and power consumption are not of concern. In this review, we compare several figure-of-merits of nanolasers and nanoLEDs, elucidating why nanoLEDs are outstanding alternatives to nanolasers as the next generation on-chip light source.

2. Modulation bandwidth

The modulation bandwidth of a LED can be calculated using Eq. (1) [25]:

$$f_{3 \text{ dB}, \max} \approx \frac{1}{2\pi} \frac{1}{\sqrt{\tau_p^2 + \tau_{sp}^2}} \quad (1)$$

where τ_p is the photon lifetime and τ_{sp} is the spontaneous emission lifetime. In LEDs, spontaneous emission is the dominant process, and photon lifetime is much shorter compared to the gain material's intrinsic spontaneous emission lifetime (~ 1 ns in III-V semiconductors, for example [25]). As a result, the modulation bandwidth of conventional LEDs is typically below 1 GHz. On the other hand, wide-bandwidth lasers (with InGaAsP length of ~ 400 μm) can reach speed of tens of GHz [26], and vertical-cavity surface-emitting lasers (VCSEL) have demonstrated modulation bandwidths exceeding 20 GHz using the optical injection locking technique [27]. Optical injection locking has also been investigated for nanolasers, and modulation bandwidth close to 100 GHz has been predicted [28]. However, no experimental attempt has been made to injection lock nanolasers yet. Lasers, nonetheless, have modulation speed that is not only limited by the spontaneous emission rate but also by gain compression. The maximum modulation bandwidth of a gain-compression limited laser can be calculated using Eq. (2) [29,30]:

$$f_{3 \text{ dB}, \max} \approx \frac{2\pi\sqrt{2}}{K}, \quad K = 4\pi^2 \left(\tau_p + \frac{\varepsilon}{v_g g'} \right) \quad (2)$$

where v_g is the group velocity, $g' = \partial g / \partial n$ is the differential gain, and ε is the gain suppression coefficient. $f_{3 \text{ dB}, \max}$ can be increased by decreasing K , which minimizes when a balance between τ_p and g' is attained. Gain compression effects can be alleviated by increasing the laser cavity size; however, a small cavity size is required to achieve high packing density in photonic ICs. To satisfy both the speed and size requirements for light sources in chip-scale optical communication systems, methods to increase speed by reducing the spontaneous emission lifetime in nanoscale light sources have been investigated intensely in recent years [25,31–38].

The spontaneous emission lifetime τ_{sp} of a nanoscale light source can be reduced through the Purcell effect, with the modification factor termed Purcell factor F

$$F = \frac{3}{4\pi^2} \left(\frac{\lambda_c}{n_a} \right) \frac{Q}{V_{\text{eff}}} \quad (3)$$

where Q is the cavity quality factor, λ_c is the resonance wavelength, n_a is the refractive index of the gain material, and V_{eff} is the cavity's effective modal volume. Because F is inversely proportional to V_{eff} , Purcell enhancement provides a method to increase the modulation bandwidth while simultaneously reducing the cavity size and effective modal volume.

In nanoLEDs, as shown in Fig. 1(a), the quality factor Q is proportional to τ_p and inversely proportional to the spontaneous emission lifetime of the cavity mode under consideration τ_{sp} , there is hence a trade-off between τ_p and τ_{sp} in their effects on modulation bandwidth as described by Eq. (1). On the other hand, decreasing V_{eff} leads to larger F , thus reduced τ_{sp} and consequently faster modulation speed. In the case of nanolasers, the Q factor is proportional to both τ_p and the differential gain g' (Fig. 1(b)), which have competing effects on the modulation bandwidth as dictated by K in Eq. (1). Fig. 1(c) shows the resulting modulation bandwidth of both nanoLEDs and nanolasers with multiple quantum well gain medium, for different V_n and Q . A nanolaser's Q factor can be as high as 1000, although typical values are below 300 [6]. On the other hand, a nanoLED's Q factor can be as high as 300, but values below 100 are to be expected for sufficiently small V_n [21]. Therefore, Fig. 1(c) suggests that nanoLEDs could actually support faster modulation bandwidth than nanolasers given an appropriately small modal volume. A maximum speed in a nanoLED is obtained with moderate Q of a few hundreds and small V_n of less than 0.01, where V_n is the normalized effective modal volume, expressed as $V_n = \frac{V_{\text{eff}}}{(\frac{\lambda_0}{2n})^3}$.

3. Threshold

In lasers, the concept of threshold is intimately linked to their coherent emission. The change of slope in the light-current curve (light-light curve in the case of optically pumped lasers) signifies the transition from spontaneous to stimulated emission. This transition, also known as the "kink", serves as a signature of the lasing threshold. In the meantime, the sharpness of the "kink" is related to the spontaneous emission factor β , defined as the fraction of spontaneous emission channeled into the lasing mode [39], and a larger β leads to a smoother "kink". In conventional lasers, β is on the order of 10^{-5} , and a sharp "kink" accompanies the onset of lasing. However, as the cavity volume reduces to the sub-wavelength scale, only a few modes exist in the spectral window of gain [40], leading to a higher β factor and a less pronounced "kink". This motivated the redefinition of the lasing threshold, or the lack thereof, in miniature lasers with near-unity β factors [39–42]. The notion of "thresholdless lasing" was consequently developed for lasers with unity β factors in which all spontaneous emission is channeled into the lasing

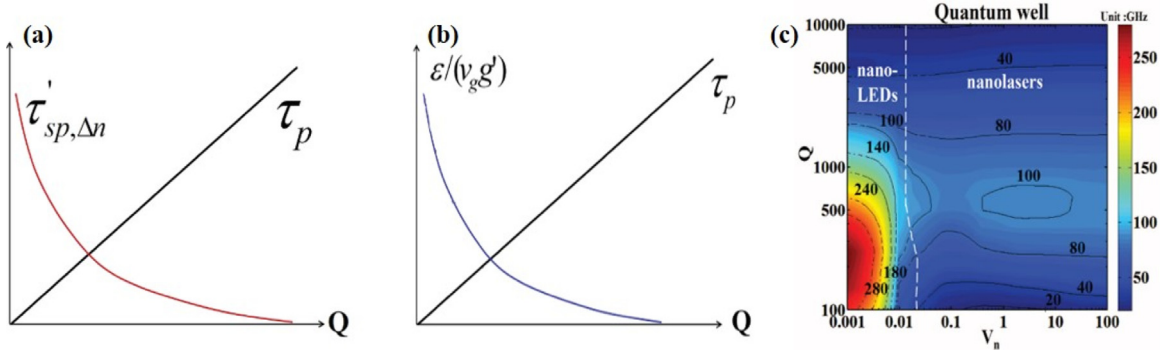


Fig. 1. (a–b) Dependence of cavity quality factor Q on (a) τ_p and $\tau_{sp,\Delta n}$ for nanoLEDs and (b) τ_p and $\frac{\epsilon}{v_g g'}$ for nanolasers. (c) Theoretical prediction of nanoLED and nanolaser modulation bandwidth. Depicted is the maximum modulation bandwidth as a function of the Q factor and normalized effective modal volume V_n . Source: Reprinted from Ref. [30] with permission.

mode, and the “kink” disappears [42]. However, because this threshold definition considers neither the balance of gain and loss at threshold nor the coherence of emission, it cannot correctly identify the transition from spontaneous to stimulated emission or the lack thereof. To this end, intricate second-order intensity correlation measurements are needed to unambiguously pinpoint the transition from incoherent spontaneous to coherent stimulated emission. This method has been experimentally employed in a few high- β nanolasers [43,44].

In nanoLEDs however, this potential misinterpretation is avoided because nanoLEDs operate solely in the spontaneous emission regime. The simplified characterization criteria give nanoLEDs an advantage when it comes to proof-of-concept and device testing. A recent study concluded that a deep subwavelength metal-clad nanoscale light source, wherein the β factor approaches unity, resembles a single-mode LED rather than a thresholdless laser [40]. The absence of lasing action is because the lasing threshold can only be reached at very high pump powers as a result of the limited volume of gain material, high metal loss, loss induced by fabrication imperfections, and damping effects caused by the augmentation of the photon density. The photon density S is related to the spontaneous emission rate R_{sp} and β factor via [45]:

$$S = \frac{\Gamma_E \beta(n) R_{sp}(n)}{\frac{1}{\tau_p} - \Gamma_E R_{st}(n)} \quad (4)$$

where Γ_E is the optical energy confinement factor, $\beta(n)$ is the carrier dependent spontaneous emission factor, $R_{sp}(n)$ is the carrier dependent spontaneous emission rate, τ_p is the photon lifetime, $R_{st}(n)$ is the carrier dependent stimulated emission rate. At deep subwavelength dimensions, the combination of the increased R_{sp} via Purcell effect and the increased β due to the reduced number of cavity modes lead to an augmented photon density. The photon density augmentation causes spectral hole burning among others, which in turn decreases the material gain $g(n, S)$ via:

$$g(n, S) = \frac{g(n_0) + g'(n(t) - n_0)}{1 + \epsilon S(t)} \quad (5)$$

where ϵ is the gain suppression coefficient, g is the gain coefficient, g' is the differential gain, n_0 is the carrier density at transparency and $n(t)$ is that above transparency. Therefore, even with a high Q factor, which is not usually the case for metal-clad nanocavities, the gain material is unable to provide sufficient gain to compensate for the losses, and ultimately, the light source can only operate as an LED [45].

Fig. 2 illustrates the direct frequency response of a nanoscale light source at different bias currents from below to above the lasing threshold, namely, as the device transitions from an LED to

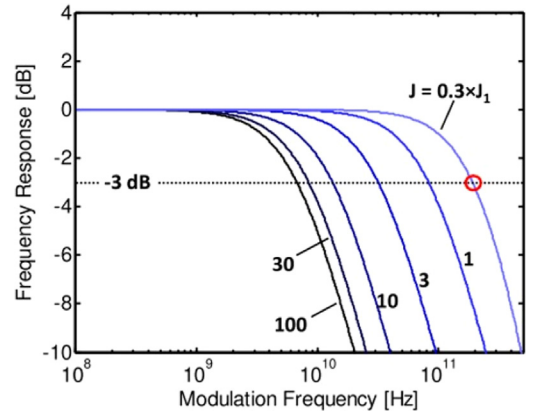


Fig. 2. Normalized frequency response as a function of different injection currents for a Purcell-enhanced nanocavity light source with $Q = 400$ and $V_n = 0.2$, reprinted from Ref. [25] with permission. The red circle indicates the largest 3 dB bandwidth ≈ 200 GHz.

a laser. Here, J_1 denotes the threshold current, and the red circle indicates the largest attainable 3 dB bandwidth. This bandwidth is obtained under a bias current of $0.3 \times J_1$ when the device operates as an LED, supporting the assertion that nanoLEDs in fact can support higher speeds than nanolasers, contrary to the case in their larger-scale counterparts [25,45].

In addition to a higher speed, nanoLEDs have the inherent advantage that the cavity loss does not need to be completely compensated by gain, as in the case of nanolasers. They, therefore, require less power to operate. Combining the advantages of nanoLEDs over nanolasers in terms of speed and efficiency, one can conclude that nanoLEDs are better suited as light sources in densely packed photonic ICs. In the proceeding sections, we overview recent advances in the design and realization of nanoLEDs, as well as their coupling to waveguides on-chip.

4. NanoLED designs

Much of nanoLED's design innovation has revolved around optical confinement and modulation bandwidth enhancement enabled by metal cladding, and a number of promising cavity designs have been explored. A few nanoLEDs demonstrating unprecedented speed or operation principles are shown in Fig. 3.

One design with potentially large modulation bandwidth and appreciable output power is shown in Fig. 3(a). Here, a PIN junction is coated with a passivation layer followed by a metal

cladding over the intrinsic region [25]. The metal creates a cavity around the physically small gain material, enabling this structure to be Purcell enhanced. A value of $V_n = 0.01$ and $Q > 10$ leads to a predicted modulation bandwidth above 100 GHz. The design, made to resemble a fin field-effect transistor (FinFET), can be scaled down to 20 nm [46], potentially satisfying the size, speed, and efficiency requirements necessary in optical interconnects.

The second design, Fig. 3(b), depicts an optically pumped shifted-core coaxial nano-emitter design [33]. In the vertical direction, the $\text{SiO}_2/\text{InGaAsP}/\text{SiO}_2$ stack forms a Fabry-Perot cavity. In the horizontal direction, the cut-off free transverse electromagnetic (TEM) mode is supported. As the metal core is shifted to one side of the cavity, the TEM-like mode gets squeezed into the narrow region between the metal core and shell, with an increased Purcell factor and a decreased modal volume compared to the un-shifted case. This design promises speed up to 62 GHz at large core-shifting distances. Although this is an optically pumped design, an electrically pumped version can be realized by incorporating doped semiconductors in the vertical direction.

Last but not least, rather than targeting optical communication applications, nanoLEDs were recently proposed as spiking-neurons in photonic neuromorphic computing systems. Fig. 3(c) presents such a spiking-neuron nanoLED design that focuses on nonlinear behavior, namely, an exponential increase or decrease of the output power with injected current [47]. This nonlinear nanoLED uses a typical metallo-dielectric design in the horizontal direction. In the vertical direction, it features a quantum resonant tunneling (QRT) layer, marked by the red line in Fig. 3(c), which enables a voltage-controlled negative differential conductance (NDC). The NDC produces a nonlinear power output operation, enabling the nanoLED to have nonlinear operating characteristics similar to lasers that are frequently proposed as “spiking neurons” in photonic neuromorphic computing systems.

In addition, a suitable nanoLED design should be capable of satisfying energy cost requirements in optical interconnects. For example, Fig. 4 (a) shows the electrically pumped version of the shifted-core coaxial nano emitter of Fig. 3(b). Here, the nanoLED is designed to support a modulation bandwidth range of 3–12 GHz, corresponding to 4.5–15.5 Gbps data rate under digital modulation (the large-signal modulation rate is 1.3 times that of its small-signal modulation bandwidth [24]). The design demonstrates an energy cost of less than 5 fJ/bit, as shown in Fig. 4(b), much lower than the system energy limit of 50 fJ/bit in the designed data rate range and at reasonable injection current levels [48]. Furthermore, the shifted core leads to highly directional emission, which, when connected with an appropriately designed waveguide, produces output power well above the thermal noise limit of photodetectors.

5. Waveguide coupled NanoLEDs

While most nanoLED designs focus on speed and efficiency, there are a number of studies that consider nanoLED’s integration with other on-chip devices, such as waveguides. Fig. 5(a) illustrates one such experimental demonstration of a waveguide-coupled nanoLED on the silicon platform. In this work, the nanoLED’s bottom-emitting output is evanescently coupled to a directional InP waveguide underneath, which is connected to a grating coupler. After accounting for the directional waveguide coupling efficiency, grating out-coupling efficiency, and setup collection efficiency, the collected power was nearly 4 nW at room temperature and 60 nW at 9.5 K [36]. In terms of speed, 5 GHz direct modulation was achieved at room temperature. Although a Purcell factor of 12 was predicted, the modulation speed was in fact enabled by the fast non-radiative recombination

rate rather than the Purcell effect, a conclusion supported by the decrease of modulation speed with decreasing temperature wherein non-radiative recombination becomes slower. Although the positive dependence of modulation speed on non-radiative recombination results in inefficient operation at high speeds, this work is pioneering. It is the first experimental demonstration of a high-speed nanoLED.

Another experimental demonstration, although not electrically pumped, is shown in Fig. 5(b). This is an antenna-enhanced nanoLED coupled to an InP waveguide. Here, the nano-LED is an InGaAsP nanoridge with a gold dipole arc antenna, which not only enhances the spontaneous emission rate but also enables high waveguide coupling efficiency due to its directionality. A 70% waveguide coupling efficiency was experimentally demonstrated with the help of the directional antenna [49]. In this design, an antenna circuit model is employed to estimate the Purcell factor [37]:

$$F = \frac{3}{2\pi} \left(\frac{\lambda_0}{d} \right)^2 \frac{R_{\text{rad}} Z_{\text{gap}}^2}{Z_0 (R_{\text{rad}} + R_{\text{ohmic}})^2} \quad (6)$$

where R_{rad} is the radiation resistance, R_{ohmic} is the ohmic resistance, Z_{gap} is the gap impedance, Z_0 is the impedance of free space, λ_0 is the free space wavelength, and d is the gap separation. The emission enhancement has a $1/d^2$ dependence, hence reducing the gap separation enhances the emission rate. The maximum coupling efficiency, on the other hand, has a $\lambda/4$ waveguide thicknesses dependence. Because this work focused on coupling efficiency and emission rate enhancement, modulation speed was not investigated.

Finally, Fig. 5(c) shows a proposal of a cavity-backed slot antenna on InP substrate. The waveguide underneath the antenna-LED is terminated with metal at one side, thus allowing unidirectional coupling of the emission into an InP waveguide on the other side. To fully utilize the emission from the fundamental mode of the antenna-LED, coupling is further improved by tapering the waveguide near the antenna-LED. Using the inverse design method, theoretical coupling efficiencies up to 94% was obtained [50]. A theoretical 3 dB bandwidth of 104 GHz was obtained with an average Purcell factor of 164. Therefore, this is another promising design to obtain a high coupling efficiency and large modulation bandwidth.

6. Conclusion

In this review, several performance metrics of nanoLEDs in relation to nanolasers are discussed to show that nanoLEDs are suitable on-chip light sources for inter and intra-chip data communication. Compared to nanolasers, nanoLEDs excel in terms of (1) energy efficiency: they operate at low bias current, unlike lasers that require high pumping level to reach lasing and to achieve large bandwidth; (2) speed: they have large modulation bandwidth enabled by a large Purcell factor, and the speed is not limited by gain compression as is the case for lasers; (3) ease of realization: they are efficient at low current injection levels, do not require low-loss cavity and are thus less sensitive to fabrication imperfections; (4) output power: they can operate under continuous-wave pumping, despite being operated at much lower injection levels; and (5) driver circuitry: they require less complex drive circuitry than lasers [21,32]. We showcased a few theoretical and experimental nanoLEDs as well as their integration with on-chip waveguides – a pivotal step in nanoLED’s insertion into chip-scale circuits.

Despite the promise, experimental demonstrations of nanoLEDs are still scarce due to fabrication difficulties on the deep subwavelength scale and characterization difficulties due to

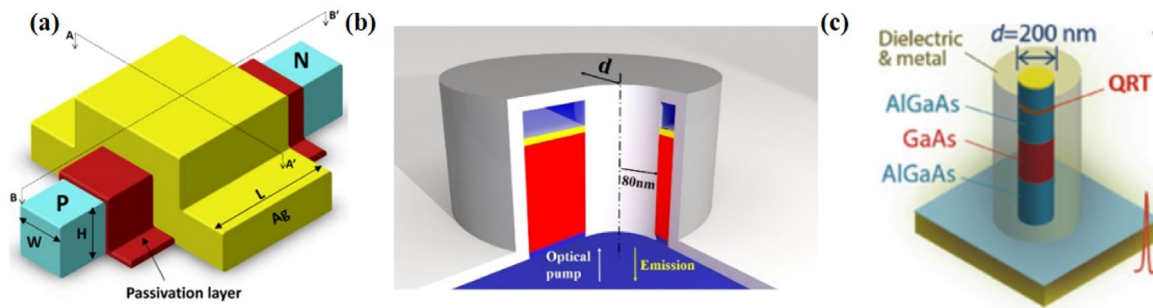


Fig. 3. Different nanoLEDs designs. (a) Fin-FET nanoLED, reprinted from Ref. [25] with permission. (b) Shifted-core coaxial nano-emitter, reprinted from Ref. [33] with permission. (c) Metal-dielectric nanoLED for high-speed spiking neuromorphic nanophotonic computing, reprinted from Ref. [47] with permission. . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

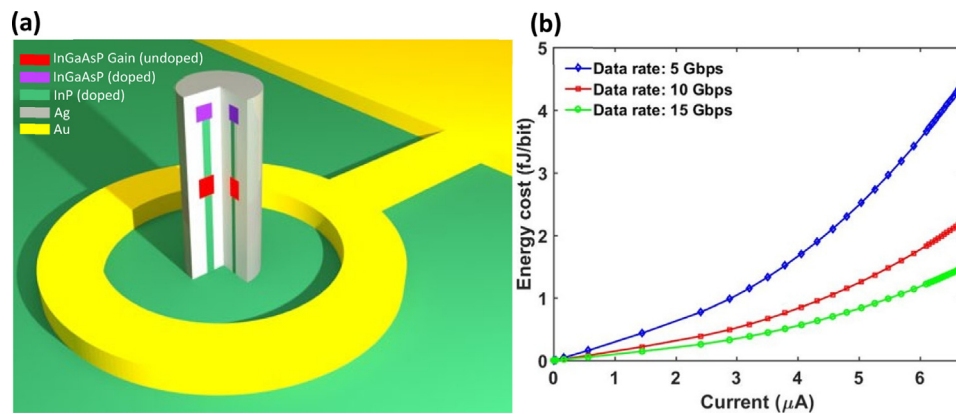


Fig. 4. (a) 3D Schematic of a shifted-core coaxial nanoLED. (b) Energy cost as a function of injection current at different data rates.

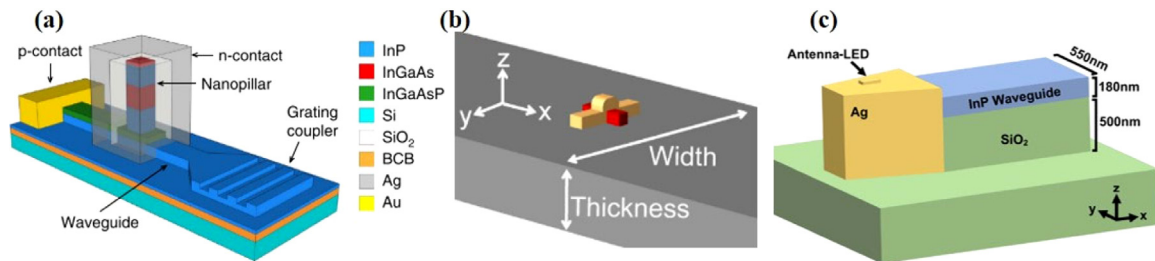


Fig. 5. Waveguide coupled nanoLEDs. (a) Nanopillar LED coupled to an InP waveguide which is connected to a grating coupler, reprinted from Ref. [36] with permission. (b) Cavity-backed slot antenna nanoLED coupled to an InP waveguide, reprinted from Ref. [49] with permission. (c) Antenna-enhanced nanoLED coupled to an InP waveguide, reprinted from Ref. [50] with permission.

the inefficient coupling of their output into characterization apparatus. With the continued advancement in fabrication and characterization techniques, an electrically pumped nanoLED with a high Purcell factor, high optical power, and high coupling efficiency to a waveguide will hopefully come to fruition soon.

CRediT authorship contribution statement

Bayron Lennin Murillo-Borjas: Wrote the manuscript, Participated in the data analysis, Improvement of the manuscript. **Xi Li:** Performed the energy cost calculations, Participated in the data analysis, Improvement of the manuscript. **Qing Gu:** Conceived the project idea, Wrote the manuscript, Participated in the data analysis, Improvement of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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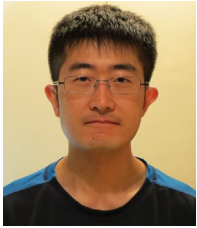
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