

Zero-Vacuum-Gap Thermophotonics

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(Received 4 July 2025; revised 9 November 2025; accepted 6 January 2026; published 29 January 2026)

Thermophotonic (TPX) devices offer a promising pathway to overcome the power density and efficiency trade-offs of thermophotovoltaics (TPVs) by using biased light-emitting diodes (LEDs) as active infrared photon emitters. However, practical implementation of TPXs has been limited by stringent demands requiring the LED to operate at high temperatures, as well as the need for near-perfect external quantum efficiency (EQE) to enable self-sustaining (i.e., no external power supply) operation. Here, we introduce a zero-vacuum-gap thermophotonic (zTPX) architecture that integrates a high-refractive-index solid-state spacer between the LED and the photovoltaic cells, which forms an optical cavity that minimizes index mismatch and enables high photon concentration. This design enhances both power density and efficiency, over 40-fold power improvement, and up to doubled efficiency enhancement compared to conventional far-field TPX, allowing the operation of TPXs at relatively lower temperatures, at which high-performance LEDs are available. Furthermore, we show that the zTPX structure achieves a record-breaking EQE of approximately 98%, which enables a self-sustaining TPX circuit with a sizable power output. These combined performance gains position zTPX as a highly practical thermophotonic solution for thermal energy conversion and utilization at low to moderate temperatures ($<1000^\circ\text{C}$), including industrial waste-heat recovery, distributed power generation, and portable heat-to-electricity converters.

DOI: [10.1103/prx.5.013005](https://doi.org/10.1103/prx.5.013005)

I. INTRODUCTION

Thermophotovoltaic (TPV) systems convert infrared thermal radiation directly into electricity by capturing photons emitted from a hot emitter onto a low-band-gap photovoltaic (PV) cell. Recent progress has improved TPV efficiencies above 40% when the emitter is heated up to extremely high temperatures ($>1500\text{--}2000^\circ\text{C}$) [1–6]. However, at low to moderate temperatures ($<1000^\circ\text{C}$), which are critical for waste-heat recovery and numerous heat sources in industrial applications, TPV performance sharply declines due to the fundamental limits imposed by the black-body-radiation law: lower temperatures significantly reduce photon flux and available radiative energy, severely constraining both the power density and the efficiency [4,6–8]. Thermophotonics (TPX), initially proposed by Green [9] over two decades ago, represents a compelling alternative to overcome the limitations of

TPV [10,11]. In TPX devices, the passive thermal emitter in TPVs is replaced by a bias-driven light-emitting diode (LED). This active emitter creates a nonequilibrium photon distribution characterized by an effective photonic chemical potential that enables emission intensities far exceeding the black-body-radiation limit. As a result, TPXs can achieve much higher power density and efficiency than TPV systems at the same operation conditions. Indeed, pioneering work has validated important aspects of TPXs. Recent theoretical and experimental advances in electroluminescent cooling have highlighted the potential of LEDs to function as solid-state heat engines, capable of photon-mediated heat extraction when operated near unity efficiency [12]. Further, a recent proof of concept by Farrel *et al.* [13] has demonstrated thermophotonic up-conversion, where sub-band-gap infrared photons have been absorbed by a hot-electron structure and reemitted as higher-energy photons subsequently harvested by a PV cell.

Despite the great potential of TPXs, no practical TPX devices have been demonstrated so far. This is due to the stringent requirements of TPXs on the LED, which cannot function and produce high light emission at even moderately high temperatures, leading to diminished power and efficiency of the TPX device. Moreover, the net power

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out of a TPX device is calculated as the power generation of the PV cell minus the power required to bias the LED, which is from either an external battery or directly from the PV cell (i.e., a self-sustaining circuit [14]). It has been estimated that even with the ultrahigh 95% round-trip efficiency of a battery system, the efficiency loss of a TPX device is substantial. Furthermore, for a self-sustaining circuit proposed by Zhao *et al.* [14], an identified barrier for practical realization is that a TPX device requires near-perfect external quantum efficiencies (EQE), approximately 98% or greater, to produce any net power. However, such EQEs significantly exceed those achieved in practice, with the most advanced LEDs and PV cells typically reaching approximately 90–96% [15–17].

To advance TPX from concept to applications, both the power density and efficiency need to be improved with novel device architectures given the limitations discovered in previous studies. One theoretical proposal to enhance the power density in TPXs is to apply the concept of near-field thermal radiation [18–29]. The near-field TPX (nTPX) concept [30], featuring submicron vacuum gaps between the hot LED and the PV cell, in contrast to the centimeter-thick vacuum or air gaps in conventional far-field TPXs (fTPXs), can increase the power density via the tunneling of evanescent waves through the ultra-thin gap. However, it is known that near-field thermal devices are very difficult to create at large scales due to the challenges of fabricating and maintaining the nanoscale vacuum gaps [31].

In this work, we propose a novel device concept to address the limitations facing TPXs. Inspired by the recent theoretical and experimental demonstration of the zero-vacuum-gap TPV (zTPV) [32,33], in which the vacuum or air gap in conventional TPV devices is replaced by an infrared transparent and high-index solid spacer, we perform a detailed analysis of the utilization of a

zero-vacuum-gap structure in TPX devices. Our approach integrates a solid-state optical spacer between the LED and the PV cell, as shown in Figs. 1(a) and 1(b). The resulting zero-vacuum-gap TPX (zTPX) device yields over 40-fold improvements in power output density compared to standard TPXs under identical conditions. Moreover, due to the high-refractive-index spacer, photon fluxes in the above-band-gap spectrum are dramatically enhanced and this increases the energy-conversion efficiency up to 100% relative to the conventional design. Notably, our design makes it possible to operate TPXs at even lower temperatures, at which typical LEDs can operate with higher performance, addressing a major limitation in current TPX design. Furthermore, the zero-vacuum-gap approach eliminates refractive-index mismatch and reflection losses at interfaces. By employing a zero-gap optical cavity with ultralow (<2%) interfacial reflectance, the zTPX system achieves an external quantum efficiency of approximately 98%, representing a substantial improvement over previously reported TPX and TPV systems and overcoming the problem in the self-sustaining TPX design. Notably, our zTPX design uses commonly available semiconductors [$\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ LEDs and/or PVs, amorphous-silicon (a-Si) spacers, and refractory-metal absorbers], that demonstrate its feasibility for scalable real-world deployment.

II. RESULTS AND DISCUSSION

A. Theoretical model and work principle of zTPX

We illustrate the structures of far-field and zero-vacuum-gap TPX devices in Fig. 1. Specifically, in an zTPX device, a biased LED is attached to a hot thermal emitter and supplies additional energy for electron-hole recombination to generate higher-intensity photon radiation on the emitter

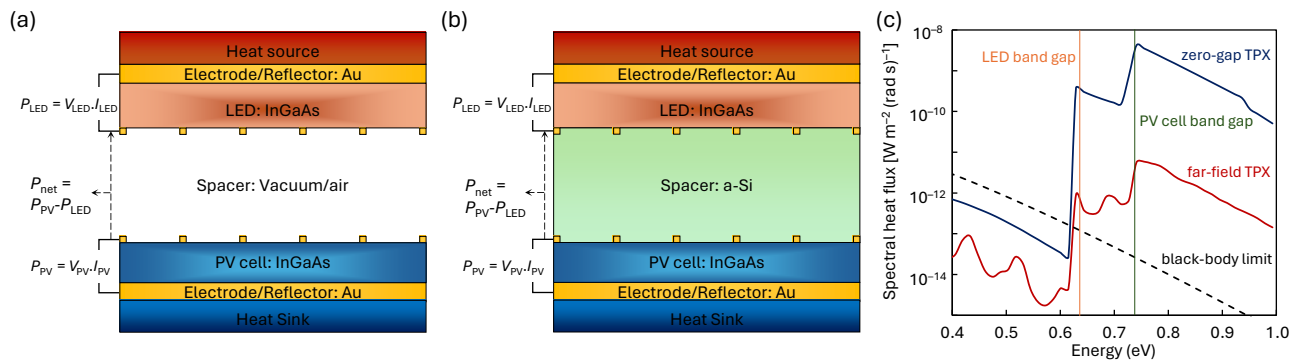


FIG. 1. The schematics of (a) far-field and (b) zero-vacuum-gap TPX design incorporating a high-index solid spacer between the hot emitter or LED and the cold reservoir. The LED and PV cell are both $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$, the back-reflector layers are Au, and the spacer material in zTPX is amorphous silicon (a-Si). (c) The calculated spectral heat flux of the far-field and zTPX designs and the black-body limit. The LED voltage for the zTPV is 0.5 V and that for the fTPX is 0.33 V. The emitter temperature is 600 K and the PV-cell temperature is 300 K. The thickness of the PV cell and the LED is 2 μm . The spacer thickness is 1 cm.

side. These photons propagate to the PV cell and generate power output. To reduce the device complexity, we have adopted the self-sustaining circuit concept, in which a portion of the generated power sustains the LED operation, while the rest is extracted as net power output [30]. The difference between zTPX and fTPX is in the intermediate layer between the LED and the PV cell. The zTPX device incorporates a solid-state optical cavity (refractive index $n > 1$). In principle, the fTPX device allows the propagating photons with parallel wave vectors in the range of $0 < k < k_0$ (where $k_0 = \omega/c$ is the free-space wave vector) to transmit through the gap. In contrast, replacing the gap with a solid spacer allows additional high-wave-vector propagating modes $k_0 < k < nk_0$ to transmit [32,33]. Furthermore, as discussed below, the existence of a solid spacer layer between the LED and the PV cell also facilitates index matching across the interfaces that results in minimized reflection, leading to very high EQE. In a TPX system, the spectral photon flux received by the LED (F_{LED}) and the PV cell (F_{PV}) can be calculated by [30]

$$F_{\text{PV}} = \int_{\omega_{c,\text{PV}}}^{\infty} \left[\frac{\Theta_{\text{LED}} - \theta_{\text{PV}}}{\hbar\omega} \Phi_{\text{LED,PV}} + \frac{\Theta_{m\text{LED}} - \theta_{\text{PV}}}{\hbar\omega} \Phi_{\text{PV},m\text{LED}} + \frac{\Theta_{m\text{PV}} - \theta_{\text{PV}}}{\hbar\omega} \Phi_{\text{PV},m\text{PV}} \right] d\omega \quad (1)$$

and

$$F_{\text{LED}} = \int_{\omega_{c,\text{LED}}}^{\infty} \int \left[\frac{\Theta_{\text{LED}} - \theta_{\text{PV}}}{\hbar\omega} \Phi_{\text{LED,PV}} + \frac{\Theta_{\text{LED}} - \theta_{m\text{PV}}}{\hbar\omega} \Phi_{\text{LED},m\text{PV}} + \frac{\Theta_{\text{LED}} - \theta_{m\text{LED}}}{\hbar\omega} \Phi_{\text{LED},m\text{LED}} \right] d\omega, \quad (2)$$

where, according to the generalized Planck's law incorporating the photon chemical potential, $\Theta_X = \theta(\omega, T_X, V_X) = (\hbar\omega / \exp((\hbar\omega - eV)/(k_B T)) - 1)$ is the mean energy of a Planck oscillator at angular frequency ω , temperature T , and voltage V . V denotes the quasi-Fermi-level splitting (photon chemical potential) divided by (e). The chemical potential term $\mu = eV$ is applied only within the LED active region and only for photon energies above the band gap, while all other layers and sub-band-gap frequencies follow the standard thermal distribution without bias [14,30,34–37]. Although typical InGaAs LEDs are often described as having a “turn-on” voltage of approximately 0.5–0.7 V, this value is not a fundamental threshold but, rather, the bias at which electroluminescence becomes observable. In our detailed-balance model, the LED emission is described using the generalized Planck law with a

photon chemical potential $\mu = eV$, which permits finite radiative emission for any forward bias $V > 0$, including $V < E_g/e$, with the emission strength decreasing exponentially as V is reduced [14,30,34–37]. The corresponding spectral heat flux of the InGaAs LED at sub-0.5-V biases is shown in Fig. S3 in the Supplemental Material [38], demonstrating finite above-band-gap emission consistent with this framework. Φ_X denotes the transmission function between different components of the TPX device, which is calculated using the multilayer-structure formalism described in the Supplemental Material [38]. In the above equation, e is the electron charge, $\hbar$ is the reduced Planck's constant, and k_B is the Boltzmann constant. After obtaining the photon fluxes, the current densities in the PV cell and the LED can be calculated as follows:

$$I_{\text{PV}} = eF_{\text{PV}} - I_{\text{Auger}} - I_{\text{SRH}} - V/R_{\text{Shunt}} \quad (3)$$

and

$$I_{\text{LED}} = eF_{\text{LED}} + I_{\text{Auger}} + I_{\text{SRH}} + V/R_{\text{Shunt}}, \quad (4)$$

where I_{Auger} and I_{SRH} represent the Auger and Shockley-Read-Hall (SRH) recombination currents, respectively, and R_{Shunt} is the shunt resistance of the PV cell and the LED (see the Supplemental Material [38]). The total radiative heat flux between the emitter and the PV cell (q_{rad}) can be obtained by integrating the net spectral heat flux as

$$q_{\text{rad}} = \int_0^{\infty} [(\Theta_{\text{LED}} - \theta_{\text{PV}}) \Phi_{\text{LED,PV}} + (\Theta_{\text{LED}} - \theta_{m\text{PV}}) \Phi_{\text{LED},m\text{PV}} + (\Theta_{\text{PV}} - \theta_{m\text{LED}}) \Phi_{\text{PV},m\text{LED}} + (\Theta_{m\text{PV}} - \theta_{m\text{LED}}) \Phi_{m\text{PV},m\text{LED}}] d\omega. \quad (5)$$

The overall efficiency of the TPX system can then be calculated as

$$\eta = \frac{P}{q_{\text{rad}} + q_{\text{cond}} - V_{\text{LED}} I_{\text{LED}}}, \quad (6)$$

where P is the power-generation density in the PV cell, given by $P = J_{\text{PV}} V_{\text{PV}} - J_{\text{LED}} V_{\text{LED}}$. q_{cond} represents the conductive heat flux between the emitter and the PV cell due to the presence of the solid spacer. It is calculated using the finite-difference method while accounting for the temperature dependence of the thermal conductivity of the spacer and the radiative absorption loss within the spacer.

To elucidate the contribution of high-wave-vector propagating waves to enhancing the power density in TPXs, we show the spectral radiation heat flux in Fig. 1(c). The radiation heat flux for photon energy above the PV-cell band gap is higher than black body in both fTPX and zTPX configurations. This is because in this regime, the LED acts as an active thermal emitter radiating super-Planckian emission. More importantly, the existence of the high-index

spacer in zTPXs exhibits a few orders of magnitude higher radiative heat flux than in fTPXs. Fundamentally, this is due to the transmission of a propagating wave with parallel wave vectors of $k_0 < k < nk_0$, which lead to high photon concentration in the cavity and enhanced radiative heat flux reaching the PV cell [32,33].

B. Enhanced power density and efficiency in zTPXs

In our following calculations, we consider a TPX system using $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ for both the LED and PV cell, and a-Si, GaAs, ZnSe, and fused quartz as the spacer in zTPXs due to their high infrared transparency, moderate-to-high index ($n > 1$) [39], and low thermal conductivity ($k = 1 - 30 \text{ W/m K}$) [40] among a large library of realistic materials that has been provided in Table S1 in the Supplemental Material [41]. The LED temperature has been varied between 400 and 900 K to theoretically assess the performance limits of TPX systems, while key discussions have focused on the 500–700 K range to maintain realism and capture the most relevant temperature effects

consistent with a previous theoretical study [30]. The efficiency and power density of zTPXs is compared with those of fTPXs in Fig. 2(a) as a function of the LED voltage for two spacer materials of a-Si and GaAs. The results show that zTPXs generate 150–320 times more power than fTPXs at the same operation condition. Furthermore, zTPXs exhibit higher efficiency over fTPXs. This is because of two key physical factors. First, the above-band-gap photon enhancement is significantly greater than the sub-band-gap radiation [as shown in Fig. 1(c)], which leads to a higher fraction of useful photons absorbed by the PV cell. Second, as the LED voltage increases, the photon emission rate grows exponentially, with a higher proportion of photons emitted above the PV-cell band gap, further improving efficiency. For the latter, it can be seen from Figs. 2(a) and 2(b) that zTPXs operate at a higher LED voltage, which increases the photon emission toward the PV cell and thereby enhances power generation via high- k waves. Based on the power density and efficiency calculated in Fig. 2(a), we define two operating conditions for TPXs: the maximal power point (P_{max}) and the

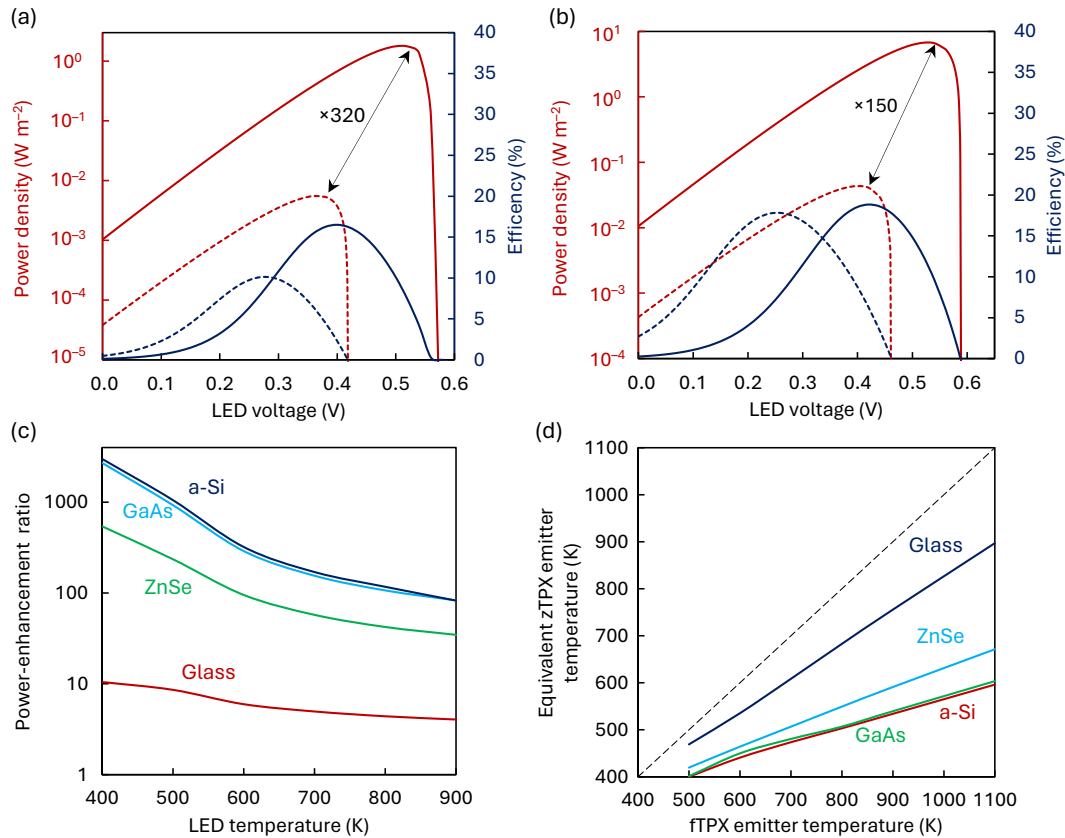


FIG. 2. The enhanced power density and efficiency in the zTPX. (a),(b) The power density and efficiency versus the LED voltage (solid lines, zTPX; dashed lines, fTPX) for (a) a-Si and (b) GaAs. The thickness of the a-Si is 5 cm and that of the GaAs is 20 cm. The LED temperature is 600 K in (a) and 700 K in (b). The PV-cell temperature is 300 K in both cases. The blue lines are for the efficiency and the red lines are for the power density. (c) The power-density enhancement in the zTPX with different spacer materials, including a-Si, GaAs, ZnSe, and glass. (d) The equivalent emitter temperature of the zTPX with different spacer materials, which yields the same power density as for the fTPX.

maximal efficiency point ($\eta_{\max}$). At these points, zTPXs deliver over 2 orders of magnitude power-density enhancement, which confirms that the zero-vacuum-gap structure is a more favored architecture for TPXs for practical applications. To see the importance of the high-refractive-index space in the zero-gap structure for power-density enhancement, we have performed simulations and compared the power-density enhancement in Fig. 2(c) for a-Si ($n \sim 3.5$), GaAs ($n \sim 3.3$), ZnSe ($n \sim 2.5$), and glass ($n \sim 1.4$). As can be seen, the enhancement ratio is highly related to the refractive index of the spacer, as by increasing the refractive index, a larger channel will be open for photons to be transferred to PV cells. However, by increasing the LED temperature, the power enhancement is decreased. This is because radiative and nonradiative losses increase with LED temperature, reducing the achieved power-density enhancement.

As the zTPX structure significantly enhances the power density and efficiency, it reduces the necessity to increase the emitter temperatures. To illustrate this clearly, Fig. 2(d) shows the equivalent emitter temperature required for zTPXs to achieve the same power density as far-field TPXs (fTPXs). According to this figure, a zTPX system operating at 600 K achieves the same power density as an fTPX device at 1000–1100 K, depending on the material spacer (a-Si, GaAs, or ZnSe). This advantage addresses a fundamental challenge in TPX systems, where lower LED operating temperatures are critical for maintaining the functionality of the LED and its high efficiency.

Despite the great potential of zTPXs in enhancing both power density and efficiency, one main potential limitation of zTPX devices is the heat conduction through the solid spacer, which is absent in conventional TPX designs. Below, we show that the benefit of the solid spacer can

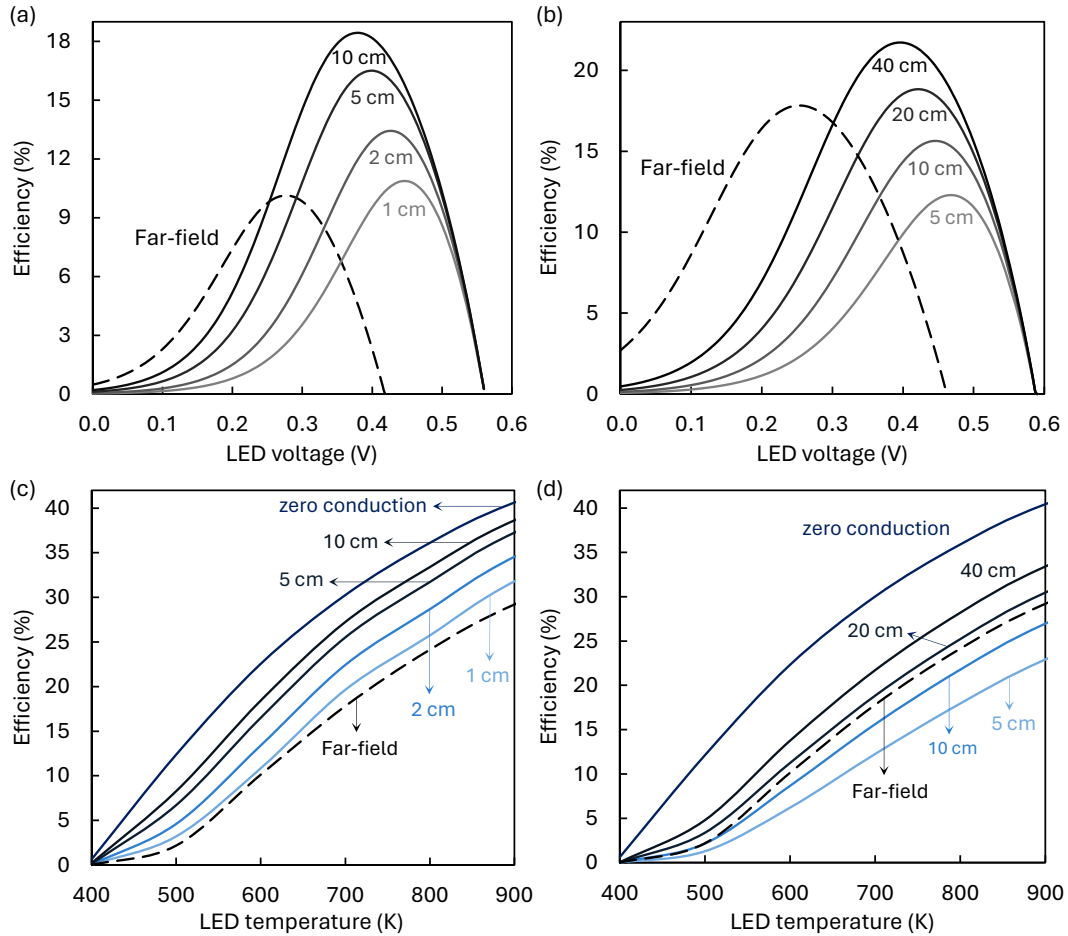


FIG. 3. The conduction effect. The efficiency of zero-vacuum-gap thermophotonic (zTPX) systems using different spacer thicknesses and materials. (a),(b) The efficiency versus the LED voltage [quasi-Fermi-level splitting (eV)] for (a) the a-Si spacer at $T_{\text{LED}} = 600$ K and (b) the GaAs spacer at $T_{\text{LED}} = 700$ K, compared with the far-field TPX configuration (dashed lines). (c),(d) The efficiency versus the LED temperature for the (c) a-Si and (d) GaAs spacers under various thicknesses.

outweigh the cost incurred by the solid spacer. In Fig. 3, we illustrate the impact of heat conduction on the efficiency of TPXs. Quantitatively, we simulate two cases, with a-Si and GaAs as the spacer. As the thermal resistance decreases, the efficiency drops due to increased thermal losses. Our calculations show that mitigating this effect using an a-Si spacer with a length greater than 1 cm or a GaAs spacer with a length greater than 20 cm, even without eliminating the heat conduction, can still enhance the efficiency. For instance, a zTPX system with a 1-cm a-Si thickness achieves nearly the same efficiency as an fTPX system. This resistance corresponds to a GaAs spacer rod with a length of 20 cm. To illustrate the impact of heat conduction, Figs. 3(c) and 3(d) compares the efficiencies of zTPXs and fTPXs at various emitter temperatures. The solid lines represent the efficiency of zTPXs, corresponding to different spacer thicknesses between 1 and 10 cm of a-Si and 5 and 40 cm of GaAs. The efficiency of the far-field TPX lies within this affected conduction region, near the lower boundary representing high conduction losses.

Despite these conduction effects, the zTPX consistently achieves higher efficiency than the conventional far-field TPX, so it shows great potential to simultaneously enhance the power density and efficiency.

C. Near-perfect EQE for self-sustaining zTPX circuits

Beyond increasing the power density and efficiency, the zTPX also exhibits a unique characteristic, as the existence of a solid-layer optical cavity also enables index matching across interfaces, which results in minimized reflection. Specifically, photons traveling from the emitter to the PV cell pass through three layers: the emitter (n_{emitter} and extinction coefficient k_e), the spacer (n_{spacer} and negligible k_{spacer}), and the PV cell (n_{pv} and k_{pv}). As shown in Fig. 4(a), our model shows that optimal index-matching-induced flux enhancement occurs when the emitter and spacer have higher indices than the PV cell (3.8), and the extinction coefficient of the emitter (k_e) is minimized to enhance index matching. Importantly, a

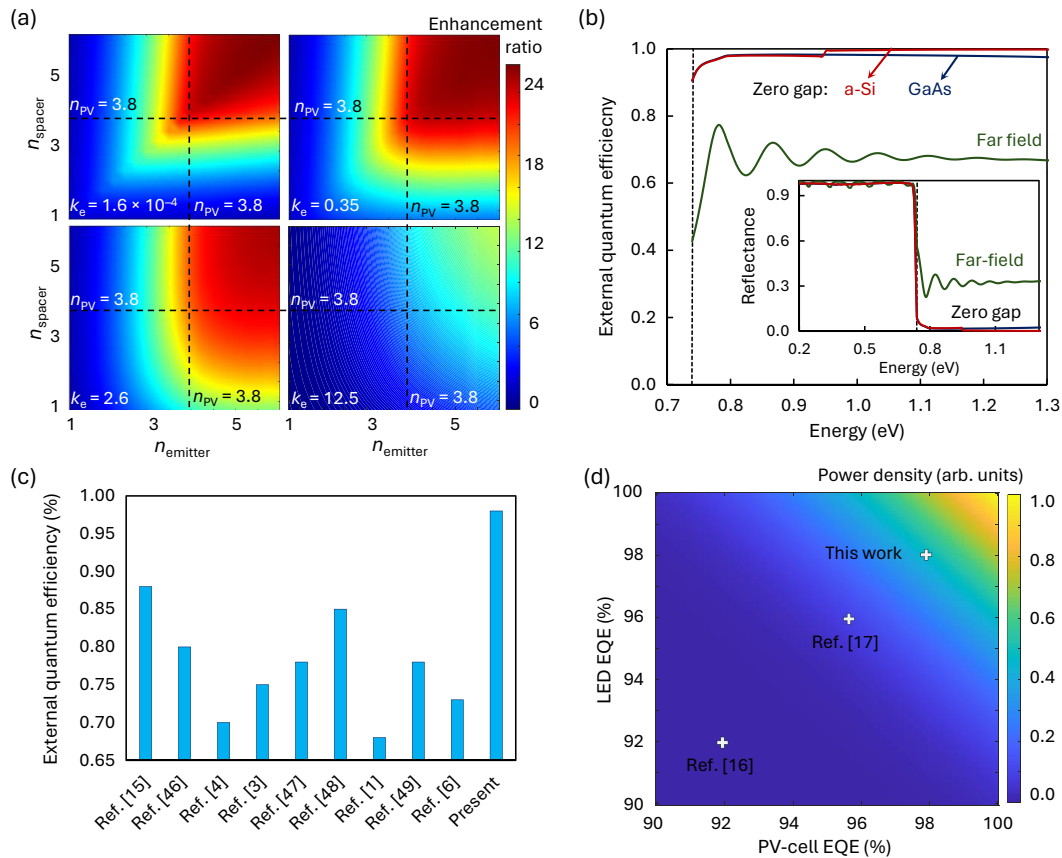


FIG. 4. (a) The radiation enhancement for varying emitter and spacer refractive indices (n_{emitter} and n_{spacer}) and the emitter extinction coefficient (k_e), using InGaAs ($n \approx 3.8$) as the PV cell. (b) The spectral external quantum efficiency (EQE) of gap-integrated far-field versus zero-vacuum-gap devices using an InGaAs cell, a GaAs-a-Si spacer, and an InGaAs emitter. (c) A comparison of the zTPV EQE with the reported far-field TPV values in Refs. [1,3,4,6,15,46–49]. (d) A contour plot showing the effect of the EQE on the power density in self-sustaining zTPX devices and the comparison of the EQE in the present work with the top values in the literature [16,17].

high index spacer alone is insufficient: both the emitter and the PV cell must also have high indices and low extinction to avoid reflection losses. Based on these criteria, we have performed calculations using a large library of realistic materials and selected $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ for the PV cell, GaAs, a-Si, ZnSe, and fused quartz (glass) for the spacer, and $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ for the emitter. In the presence of index matching, we predict over 20 times heat-flux enhancements enabled by the zero-vacuum-gap structure. The index matching via the coupling of a solid spacer and an emitter or PV cell naturally leads to anear-perfect EQE. The EQE is the fraction of photons incident on the PV cell that generate electron-hole pairs and contribute to power generation. It is related to the internal quantum efficiency (IQE) by $\text{EQE} = \text{IQE} \times (1 - R)$, where R is the reflectivity. While recent studies have demonstrated high IQE, the air or vacuum gap in far-field TPV and TPX devices has fundamentally prohibited a near-perfect EQE due to index mismatch [42], leading to substantial power losses. Although near-field TPX systems can access high- k evanescent modes, these modes do not eliminate the strong reflection arising from the refractive-index discontinuity between the semiconductor and vacuum. In contrast, the zero-gap configuration intrinsically removes this mismatch, allowing almost all photons to enter the PV cell. EQEs in current TPV devices are only 60–70% [1,4,6] and the highest reported EQE in a TPV device is 88% [15]. As shown in Fig. 4(b), we have found that in a zero-vacuum-gap structure using readily available materials ($\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{GaAs}/\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ and $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{a-Si}/\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$), the total interfacial reflectance can be reduced to less than 2%. This results in a record EQE of 98%. This demonstrates one of the key advantages of zero-vacuum-gap heat engines to enable TPX applications. In particular, in the proposed self-sustaining TPX circuit, multiple PV cells and LEDs are connected in series, with these groups arranged in parallel and connected to a load. This enables continuous energy extraction while sustaining LED operation (for details of the self-sustaining TPX model, see the Supplemental Material [38]). However, as described in Ref. [14], for a self-sustaining TPX system to function, it must meet very strict EQE requirements. In Fig. 4(d), we show that the power density drops sharply when the EQE of the PV cells and LEDs falls below 97%. To maintain net power generation, both components must achieve at least 98% EQE, which is an almost unattainable goal with current gap-based TPX designs. It should be noted that Fig. 4(d) is calculated based on the theoretical framework developed by Zhao *et al.* [14]. We have directly adopted this model without modification to evaluate the achievable performance of the zero-gap TPX configuration at higher EQE values, providing a consistent comparison with prior theoretical work. As shown in Fig. 4(d), the index matching and ultralow interfacial reflection of zero-vacuum-gap

structures enable the zTPX to exceed this EQE threshold, which makes it the configuration capable of supporting a viable self-sustaining TPX system.

III. CONCLUSIONS

We have proposed a new device architecture to enable practical thermophotonic applications in the low to moderate temperature range with high efficiency and power output potential. By replacing the traditional vacuum or air gap with a transparent high-refractive-index solid spacer, the present zero-vacuum-gap structure, called zTPX, overcomes long-standing limitations in power density and efficiency in conventional TPXs. Our results show that the zTPX outperforms the far-field TPX by over an order of magnitude in power density, while simultaneously achieving significantly higher energy-conversion performance (doubling the efficiency). Unlike the near-field TPX, which suffers from fabrication complexity and gap-control challenges, the zTPX leverages far-field wave propagation through a solid cavity, making it more robust, scalable, and easier to integrate into practical devices. The high EQE of approximately 98% induced by the index-matching effect in the zTPX surpasses the threshold required for self-sustaining TPX circuits, a critical milestone for eliminating external power sources and enabling compact closed-loop energy converters. The proposed zTPX system also offers a path toward material-agnostic and thermally robust operation. The design relies on commercially available materials such as $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$, a-Si, and refractory metals, and remains effective across a wide low-to-moderate temperature range (400–1000 °C), which aligns with industrial waste-heat and midgrade thermal-energy sources. Additionally, while heat conduction through the solid spacer can introduce efficiency losses, our analysis reveals that this effect is less of a concern for thick and thermally insulating solid spacer materials such as a-Si and diminishes at elevated temperatures due to the stronger scaling of radiative heat transfer with temperature. The zTPX opens up new opportunities in the design of solid-state photonic heat engines and power generators for remote, portable, or distributed energy applications. Future work may focus on experimental realization of a zTPX circuit integrated with thermal storage systems, and optimization of material combinations to further enhance spectral selectivity and thermal robustness.

ACKNOWLEDGMENTS

L.C. acknowledges support from the National Science Foundation (NSF) (Grants No. 2239004 and No. 2343027), the NSF I-Corps program (Grant No. 2311324), the Colorado Office of Economic Development and International Trade (Grant No. OEDIT DO 2024-2320), and the Lab Venture Challenge Prize at University of Colorado

Boulder. This work has utilized resources from the University of Colorado Boulder Research Computing, which is supported by the NSF (Grants No. ACI-1532235 and No. ACI-1532236), the University of Colorado Boulder, and Colorado State University.

DATA AVAILABILITY

The data that support the findings of this paper are not publicly available. The data are available from the authors upon reasonable request.

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