Low-power communication with a photonic heat pump

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Abstract: An optical communication channel is constructed using a heated thermo-electrically pumped, high efficiency infrared light-emitting diode (LED). In these devices, electro-luminescent cooling is observed, resulting in greater than unity (> 100%) efficiency in converting electrical power to optical power. The average amount of electrical energy required to generate a photon (4.3 meV) is much less than the optical energy in that photon (520 meV). Such a light source can serve as a test-bed for fundamental studies of energy-efficient bosonic communication channels. In this low energy consumption mode, we demonstrate data transmission at 3 kilobits per second (kbps) with only 120 picowatts of input electric power. Although the channel employs a mid-infrared source with limited quantum efficiency, a binary digit can be communicated using 40 femtojoules with a bit error rate of 3 x 10^{-3}.

OCIS codes: (030.5620) Radiative transfer; (260.2160) Energy transfer; (230.3670) Light-emitting diodes; (190.4870) Photothermal effects.

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1. Introduction

The topic of minimum energy requirements for transmitting a bit of information dates back to Shannon's work in the 1940s [1]. Applying Shannon's work to electro-magnetic communication, in which blackbody radiation behaves as additive white Gaussian noise, results in the well-established Landauer limit of $k_B T \ln(2)$ per bit [1–6]. Here, we highlight the difference between sending a binary digit '0' or '1' across a physical noisy channel with some finite bit error rate (BER) and sending one bit worth of mutual information, for which there is no BER. The Landauer limit describes the latter case. It represents a theoretic bound for the average energy used per bit of information entropy shared across a channel which uses coding to achieve arbitrarily small BER [1]. In the case of an optical link between two electronic systems, the signal sequentially undergoes multiple transformations. A typical sequence may include (1) digital-to-analog conversion of the electrical signal, (2) electrical-to-optical conversion of the analog signal, (3) transmission of the optical signal from source to receiver, (4) optical-to-electrical conversion of the analog signal, and (5) amplification and analog-to-digital conversion of the electrical signal at the receiver. The Landauer limit indicates a minimum amount of energy which the physical signal must possess per bit of information it contains, and applies equally to each of the processes in the typical sequence above. In this work, we address the limits of energy efficiency in steps (2) through (4). Here the efficiency of electrical-to-optical power conversion is critical to minimizing the energy consumption of the devices which perform these operations.

The well-known Landauer limit for the minimum energy of $k_B T \ln(2)$ needed to communicate a bit of information at temperature T across a linear channel applies even for a thermophotonic infrared light-emitting diode (LED) where the energy cost of producing a single photon may be less than $k_B T \ln(2)$. Thermophotonic LEDs achieve high efficiency with low brightness. This low brightness requirement ensures that this optical signal is immersed in noise from background thermal photons in such a way that multiple signal photons are needed to encode a single bit of information. Despite this low photon efficiency, we present the results of using such an LED as an extremely energy efficient source in a communication channel.

Recently, LEDs have been observed to exhibit greater than unity efficiency in converting electrical power to optical power [5]. These experimental results verified the longstanding theoretical claim that lattice heat can help pump electrons in the light-emitting device, making possible the twin phenomena of net cooling of the diode's semiconductor lattice and > 100% wall-plug efficiency [7,8]. While LEDs can operate at extremely high efficiencies, existing devices only do so in the low-bias regime, an operating range in which the average electrical energy qV used to push an electron across the diode is less than the average thermal energy $k_B T$ of the device. In this regime, the current I, the voltage V, and the emitted light power L of the device are all linearly proportional; as a result we find the wall-plug efficiency

$\eta = L/(IV)$ to be inversely proportional to L. In one of these experiments [9], the wall-plug efficiency of an infrared LED (λ ≈2.5 μm with a spectral width confirmed by FTIR to be approximately 300 nm) heated to 150°C was found to be as high as $\eta = (5700 \pm 1600)\%$. Such results lead us to believe that they may prove useful for certain low power optical communication systems, especially those for which power consumption on the source side of the channel is a significant constraint for the system, as is often the case with remote sensor networks [10]. Furthermore, the LED outputs an optical signal that is much less than the average power of ambient blackbody radiation at the emission wavelength, similar to scenarios found in quantum optical communication [11–13], and potentially useful for covert communication applications [14].

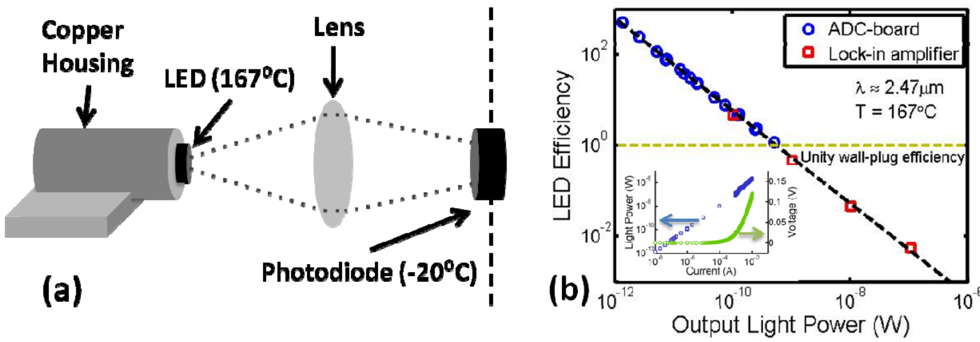

Fig. 1. (a) An illustration of the free-space optical channel used in this experiment. Light from an $In_{0.15}Ga_{0.85}As_{0.13}Sb_{0.87}$ LED emitting at 2.5μm at 167°C is collected using a cooled InGaAs photodiode operating at zero bias. (b) Wall-plug efficiency versus emitted optical power for the LED. This data was acquired using two different receiver circuits: a digital lock-in amplifier and a 16-bit analog-to-digital converter. Both measurements indicate an inverse relationship between efficiency and light power. The inset shows L-I and I-V curves for the LED, using a combination of the ADC and the lock-in for low bias conditions, and a DC measurement at high bias conditions. We note that in modeling the LED, the collector efficiency was a fitting parameter [5]. Therefore, any uncertainty in converting photocurrent at the detector to optical power would appear equally in both the data and the model, but would not affect the 1/L power-law relationship between efficiency and power.

We used such an LED heated to 167°C as the source in the optical channel depicted in Fig. 1(a). The efficiency in the low-bias regime is plotted in Fig. 1(b) and demonstrates the inverse relationship between efficiency and light power, as illustrated by the dashed line. In [5], light detection was performed with the aid of a lock-in amplifier; here we use an analog to digital converter (ADC) offering faster sampling and sufficient flexibility for optical communication. By applying a discrete Fourier transform to the sampled time-domain data, we were able to extract the magnitude and phase of the frequency component phase locked to the modulation frequency of the signal in order to in order to ensure this signal was properly separated from any photo-current due to background thermal radiation, which is approximately white and thus has no preferential phase relationship to the source-side modulation. Because we elected to cool the detector to −20°C to reduce its noise-equivalent power (NEP), we are able to detect even lower light levels and even higher efficiencies than before. We were able to detect 7.66 ± 1.6 pW of light power at a wall plug efficiency $\eta = (8000 \pm 1700)\%$. At these operating conditions, the amount of energy required to generate a photon of energy $\hbar\omega$ = 520 meV is just 4.3 meV of input electrical energy, which is well below $k_B T \ln(2) \approx 25$ meV at the source temperature of 167°C. Even if the Landauer limit energy of the channel is set by the cooler detector temperature, $k_B T \ln(2)$ is still 15 meV.

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The possibility of communicating a photon for less than $k_B T \ln(2)$ immediately raises questions about which, if any, of the typical assumptions has been violated. First of all, the difference in temperature between source and detector means the overall channel is not in thermal equilibrium when off. However recent measurements demonstrating room-temperature LED operation well above 100% wall-plug efficiency indicate that the aforementioned scaling laws between efficiency and power remain valid even when this temperature gradient is removed [15]. Alternatively we may notice that while a thermophotonic LED can emit a photon with fixed energy while consuming arbitrarily little electrical energy, the associated power constraint means it may not be possible to produce and detect these photons with enough certainty to communicate an entire bit of actual information content with each photon. On this topic, we point out a fundamental trade-off between entropy and information content in our channel. When the LED is operating above unity efficiency in low-bias, it draws power from an entropy-free electrical source as well as the entropy-carrying thermal reservoir to generate an entropy-carrying optical output. As the amount of input electrical power is reduced, the emitter relies increasingly on the entropy-carrying thermal reservoir and the resulting photon flux becomes difficult to distinguish from the background blackbody radiation, indicating an optical signal with low signal-to-noise ratio and thus low information carrying capacity. This trade-off between the physical entropy within a finite signal and the information content it carries manifests itself as a low photon efficiency (bits per photon) when the photon energy cost (Joules per photon) is low.

We have constructed a communication channel in which the energy per binary digit is less than one picojoule. In calculating the energy per bit of the communication channel, we omit energy used to maintain the temperatures of the emitter and detector because the phenomenon we are exploiting in principle allows this energy to be zero [15]. Instead we include only the electrical energies needed to operate the optical channel. More specifically, since the photodiode detector is operating at zero voltage bias, our input energy costs consist only of the electrical energy supplied to the LED. In keeping with the context of demonstrating efficient operation of just the optoelectronic components in a link, we do not include energy costs of the electrical amplifiers, analog-to-digital or digital-to-analog converters, or the source encoder. Finally, while the data rate of our channel is low, in the tens of kilobits per second (kbps), we note that this limitation is set not by the opto-electronic components but rather by the 50 kHz bandwidth of the particular trans-impedance amplifier used here. The typical switching speed of the LED is 20 ns [16], suggesting that higher data rates could be achieved with optimized amplification hardware. In the following sections, we outline the protocol for the communication of bits across our channel, and subsequently demonstrate optical communication at very low power.

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2. Methods

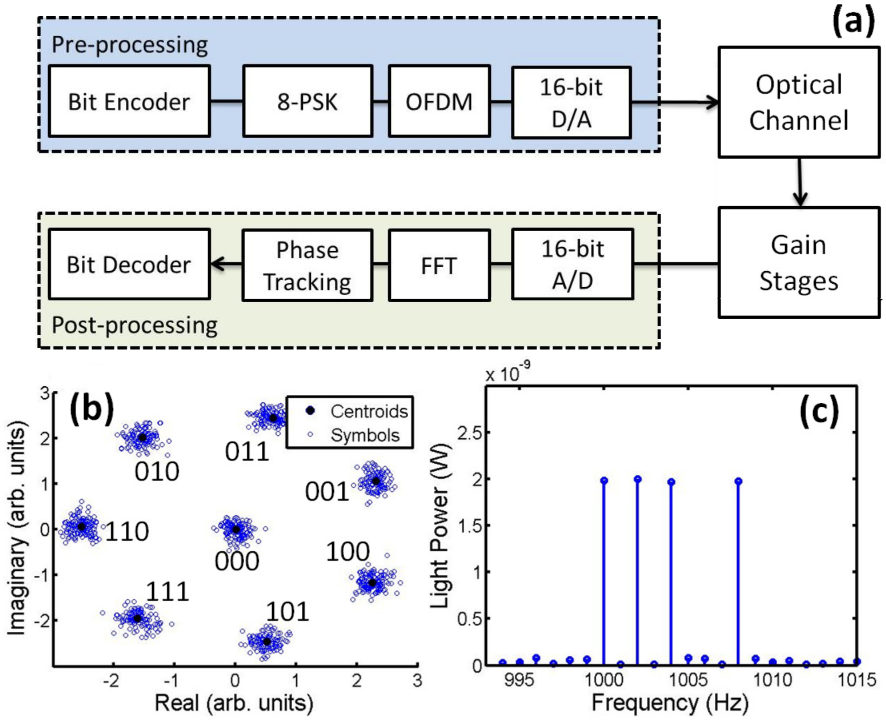

Fig. 2. (a) Block diagram of the LED communication channel. (b) 8-symbol phase shift keyed coding with seven symbols equally spaced in phase, and the last symbol at zero magnitude. The centroids of each symbol are also labeled. (c) Received signal from an orthogonal frequency division multiplexed (OFDM) channel depicting orthogonal channels with 1Hz spacing; channels at 1000, 1002, 1004, and 1008Hz are transmitting nonzero symbols.

To characterize our optical communication channel, we transmit a sequence of randomly generated bits. The apparatus to transmit a bit with this channel is illustrated in Fig. 2(a). We implemented phase-shift keying (PSK) methods to maximize the use of available spectrum. In this experiment, we used both quadrature phase shift keying (QPSK) with four phases ($N = 4$) and a higher-order version (8-PSK) using eight phases ($N = 8$) as coding schemes. For 8-PSK, we group every sequence of three bits together and assign it one of 8 possible symbols. However, instead of placing all 8 symbols spaced equally in phase as designated by the conventional scheme, we placed 7 of the symbols to be equally spaced in phase and the last symbol is placed at zero magnitude and phase, as seen in Fig. 2(b). These symbols are assigned by minimizing the Hamming distance between two adjacent symbols. The zero symbol is representative of when the LED is off, and thus it reduces overall power consumption.

We also employed orthogonal frequency division multiplexing (OFDM) as a modulation scheme for this experiment to maximize the use of effective bandwidth [17]. OFDM is a method to split up a single, high data-rate channel into many parallel, slower channels, each of which is at a frequency orthogonal to all other channels, as depicted in Fig. 2(c). The PSK symbols are therefore encoded directly into the frequencies by toggling the channel at that frequency on or off depending on the whether the symbol has a nonzero magnitude or not. This scheme allowed us to avoid persistent noise spikes at certain frequencies that are artifacts of the amplifiers and the laboratory environment by not including such frequencies as channels in our protocol. Due to the linearity of the device in the low-bias regime and the

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orthogonality of the frequencies, we were able to superimpose all the input channels to the device without significant intersymbol interference.

A precomputed waveform carrying the encoded bit stream is input to a 16-bit, 1 mega-sample per second (MS/s) digital-to-analog converter (DAC) to create a voltage waveform that is applied across the LED in series with an external 5kΩ resistor. Because the zero-bias resistance *R* of the LED is only 27Ω at 167°C, only 0.5% of the total voltage is dropped across the diode. Since the 5kΩ resistor dominates the load, it also controls the current and thus the LED is approximately current-biased. The total current through the LED may then be written in terms of the sequence of *M* normalized (i.e. magnitude 0 or 1) complex-valued PSK symbols $\{B_i\}$ and their corresponding OFDM frequencies $\{f_i\}$ as:

$$I_{LED}(t) = \sum_{i=1}^{M} \Big[|B_i| \cdot I_0 \cos\big(2\pi f_i t + \arg(B_i)\big) \Big] \tag{1}$$

Note that Eq. (1) permits the LED drive current to be negative at times. A negative current flow indicates a small reverse bias across the LED, resulting in a reduction in spontaneous radiative recombination as some of the carriers are flowing backwards toward the contacts and through the power supply instead of undergoing radiative recombination. By restricting the channel waveforms to be zero-mean sine waves, we were able to maintain linearity in the device and use many channels in parallel without affecting the operating point. The efficiency of the device remains the same regardless of whether there is 1 channel or 1000 channels as long as the device is operating in low-bias throughout the duration of the signal. This low-bias operation can be ensured with proper selection of I_0, the current modulation amplitude for each frequency component, such that the LED remains in low bias the vast majority of the time for a high-entropy random bitstream. Thus, we were able to use OFDM to maximize our bandwidth efficiency while maintaining the same device power conversion efficiency as is evident from a direct calculation of the energy used to generate the signal. The electrical energy *E* used to operate the channel for one OFDM temporal block length t_s is:

$$E = \int_0^{t_s} |I_{LED}(t)|^2 \, R dt = \frac{I_0^{\,2} R}{2} \cdot t_s \cdot \sum_{i=1}^{M} |B_i|^2 \tag{2}$$

The optical power is detected using an InGaAs photodiode and amplified through a trans-impedance amplifier and a low-noise voltage amplifier with combined gain of 5×10^6.The resulting voltage waveform is sampled with a 16-bit ADC operating at 500kS/s and processed with a fast Fourier transform (FFT) algorithm to separate the signal's orthogonal frequency components associated with each channel. To create a decoder for the FFT output, we first send a test sequence of symbols, and record the complex amplitudes of each frequency component. We then employ a phase tracking algorithm that corrects for the linear phase shift with frequency of the signals due to filters present in the amplifier chain. We then take note of each symbol's location in the complex plane, and assign a centroid location for each symbol. Next, when we send sequences of random symbols, we identify a symbol encoded in a given channel by finding the closest centroid. Finally, we decode the symbols back into a binary digit sequence and check for errors.

3. Results and discussions

We report using the described experimental apparatus to transmit digital information across a free-space optical channel at three different data rates: 3, 30, and 90 kilobits per second (kbps). The symbol rate for each channel was $1/t_s$, and the bit rate was twice or three times the symbol rate, depending on whether 4-PSK or 8-PSK was used respectively. Finally, since we used approximately M = 1000 OFDM channels to carry the symbols, the overall symbol rate of our communication link was M/t_s and the overall bitrate was again two (4-PSK) or

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three (8-PSK) times this value. To increase the data rate of our channel, we decreased t_s and correspondingly increased the modulation frequencies $\{f_i\}$ so as to retain orthogonality over this interval. As expected, increases in data rate thus required the use of additional bandwidth.

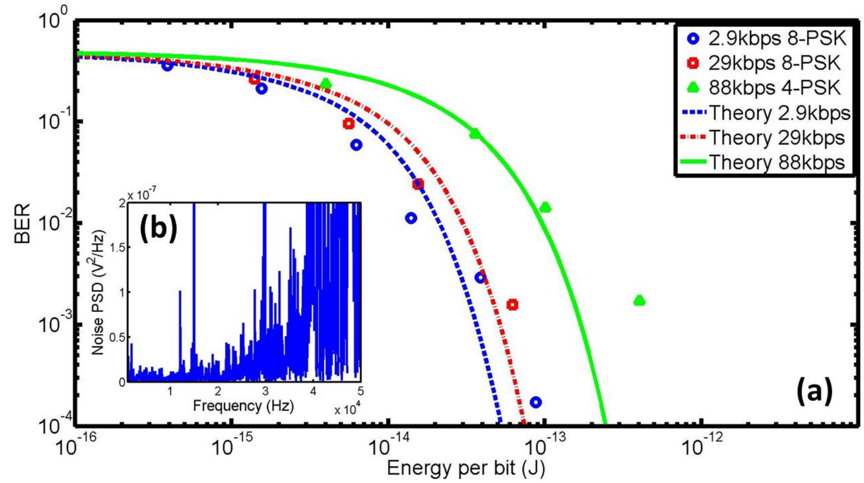

Fig. 3. (a) Bit error rate (BER) versus energy per bit at various data rates. The curves show the theoretical bit error rate assuming a flat noise power spectrum and varying the magnitude of the current signal driving the LED. Input power can be related to energy per bit by Eq. (2). (b) The inset containing the noise spectrum of the channel indicates more noise at higher frequencies. Higher data rate experiments showed higher bit error rates at a given energy per bit as a result.

The results of the experiment operating at three different data rates are shown in Fig. 3(a). The electrical energy per bit required for each transmission was calculated using Eq. (2). The bit error rate for each transmission was found by direct comparison of the final decoded data against the data encoded in the initial waveform. Bit error rates under 10^{-4} could not be accurately detected since only 10000 bits were sent in each sequence. This is purely a limitation due to testing procedures, and does not represent the physical limit of the system. We present experimental results for bit error rate versus energy per bit of three modulation schemes alongside theoretical calculations of BER which assume a flat noise spectrum. For each data rate, the theoretical calculations are made taking the noise equivalent power (NEP) as the average of the measured values in each active channel, and taking the optical power available at unity wall-plug efficiency to be 533 pW as shown in Fig. 1.

For the slowest data rate of 3 kbps with 8-PSK modulation, we observe a BER of 3 x 10^{-3} for 40 fJ of input electric energy per bit. With M = 1000 orthogonal frequencies used in parallel, the total electrical power consumption is 120pW. We find the BER increases as we decrease the energy per bit as expected, since the amount of light power per channel decreases, and it becomes harder to distinguish the different symbols. The most efficient operation observed used 0.39fJ per '0' or '1' with an error rate of 36%. We note that each '0' or '1' decoded by the receiver at this operating point contains significantly less than one full bit of information from the source. However, since this error rate is still below the error rate of 50%, the channel is still communicating some information. At the other extreme, the rapid decrease in BER as the energy increases can be extrapolated (assuming that the noise is constant) to an energy per bit less than 100 fJ/bit even for a BER equal to 10^{-10}.

As the data rate of the channel is increased, the BER for a given energy per binary digit also increases, as seen in the comparison of 30kbps and 3 kbps for the same 8-PSK modulation. This is due to the NEP of the detector and subsequent amplifier chain not being uniform across all frequencies, as depicted in Fig. 3(b). In our experiment, we find the noise-equivalent power spectral density increases up to 50 kHz; frequencies above 50 kHz were not characterized because our amplifiers lacked sufficient gain to use them in our channel. As we increase the data rate of the system and extend the bandwidth in which the signal exists to higher frequencies, we therefore expect more noise and higher error rates as observed.

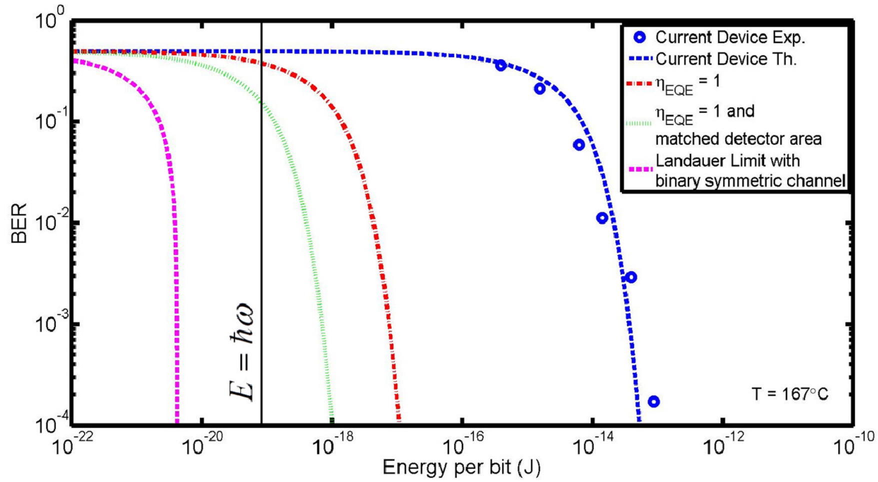

Fig. 4. Bit error rate (BER) versus the energy per bit for the experimental channel, as well as extrapolations for an idealized LED-detector pair. All three curves assume 8-symbol phase shift keying.

In Fig. 4, we have taken the data from the 3 kbps rate and extrapolated to two interesting limits, both of which can be asymptotically approached in physical systems. The first criterion is the external quantum efficiency of the device η_{EQE}. In our device, the measured η_{EQE} is approximately 2 x 10^{-4}; in principle this figure can approach one. Because the wall-plug efficiency of the device increases linearly with its quantum efficiency, we extrapolate using an inverse relation between energy per bit and external quantum efficiency for the same BER. The second criterion that we have considered is the collection area of the photodetector. In the experimental setup, the detector element of the photodetector (3 mm diameter) is much larger than the active region of the LED (280 μm diameter). If we were instead to have a matched detector with the same detectivity, we would see a further decrease in BER for the same energy per bit due to a reduction in the shunt conductance at the first amplifier stage, which currently sets the noise floor. Combining these two criteria results in an extrapolation that approaches the Landauer limit at 167°C. Once again, we point out the difference between $k_B T \ln(2)$ which would be a vertical line at 4.2 x 10^{-21} J and the Landauer limit for a mutual bit of information, which is plotted assuming a binary symmetric channel and taking into account the finite BER.

Further extrapolations may also be physically possible and present interesting questions. For example, in our measurements, the NEP was dominated by the dark current of the detector rather than the blackbody radiation from the source. As we cool the detector, we find that the NEP drops even further, signaling that we are not in the regime where incident blackbody radiation is the dominant source of noise. It is unclear what the relationship between BER and energy per bit will be at very low detector temperature. We believe that many of the fundamental limits set by the blackbody radiation and entropy of the light source will be apparent in this regime, and propose this as an interesting research topic for the future.

In summary, we have demonstrated communication at a bit error rate of 3 x 10^{-3} for 40 femtojoules per bit using an extremely efficient thermo-electrically pumped (or thermophotonic) mid-infrared LED operating at low bias at 167°C. This energy per bit is comparable to recently reported semiconductor diode laser technologies [18]. State of the art vertical-cavity surface-emitting lasers operate around 56 fJ/bit [19] while photonic crystal nanocavity lasers have been reported to operate with as little as 4.4 fJ/bit [20]. Recent results using modern nanophotonic techniques have demonstrated 0.25 fJ/bit communication with a single mode photonic crystal nanocavity LED [21]. However, we note that our approach to efficient communication is fundamentally different and scales with bitrate differently as a result. The aforementioned devices demonstrate a low energy per bit by achieving high modulation speeds of 10 Gb/s or higher while consuming microwatts of input power. Our device is able to achieve a comparable energy per bit despite transmitting at just a few kilobits per second because it only consumes picowatts of input power. For a low-bias LED, the electrical power consumption scales linearly with the bitrate as the latter is reduced toward zero. This contrasts with channels using laser sources where there is a fixed electrical power required to achieve laser threshold. Such operating performance may be of particular benefit for battery-powered sensors. We have considered idealized LEDs and detectors, and extrapolated from our data to find that the energy per bit in such channels could be on the order of the Landauer limit. Based on these results, we believe that this LED based communication channel can serve as a platform to explore the theoretical bounds of energy efficient communication.

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