Energy dissipation in energy transfer mediated by optical near-field interactions and their interfaces with optical far-fields

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Energy efficiency is one of the most important aspects of today’s optical technologies.1–4 Energy efficiency of optical processes has been highlighted in the context of exploiting the low-loss, wavelength-multiplexed, high-bandwidth nature of optical communications.5 Another feature of photons for efficient energy usage is their unique attributes exhibited on the nanometer scale, namely, energy transfer mediated by optical near-field interactions between quantum nanostructures.1 Nanophotonic devices based on optical near-field interactions have been experimentally demonstrated at room temperature based on stacked quantum dots (QDs).5 Previously, we have theoretically analyzed the lower bound of energy dissipation required for elemental optical excitation transfer from a smaller QD to a larger one by analyzing the energy dissipation occurring at the destination quantum dot.1 The purpose of the study described in this letter is to analyze the energy dissipation in energy transfer via optical near-field interactions as a total system, including the energy dissipation of the input and output interfaces with optical far-fields, while considering the number of photons required for photodetection. The lower bound of total energy dissipation was estimated to be 138 eV theoretically and 155 eV experimentally, which are both about 104 times more energy-efficient than electronic devices. We also examined some fundamental differences between near-field-mediated optical energy transfer logic and electrical logic in terms of energy dissipation. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4729003]

We theoretically and experimentally evaluated energy dissipation of nanophotonic devices based on energy transfer via near-field interactions and their interfaces with optical far-fields. The lower bound is about 104 times more energy-efficient than electronic devices. We also examined some fundamental differences between near-field-mediated optical energy transfer logic and electrical logic in terms of energy dissipation. © 2012 American Institute of Physics.

signal flow from QD1 to QD2. Such energy transfer enables versatile functionality, such as nanophotonic logic gates6,7 or energy concentration.6,7 When we operate these nanophotonic devices, input and output interfaces are needed in practice. Figure 1(b) schematically represents a system model considered in this letter, composed of (i) an input interface converting an optical far-field to an optical near-field, (ii) a nanophotonic logic device (e.g., a NOT gate), and (iii) an output interface converting the optical near-field to the optical far-field, followed by a photodetector.

The input interface can be realized by multiple combinations of energy transfer, called an optical nanofountain7 or cascaded energy transfer (CET),8 as schematically shown in the left hand side of Fig. 1(b). The conversion efficiency from the input optical energy to the largest QD in the system is known to be high, similarly to a light harvesting antenna.8 The energy dissipation associated with such input interfaces involves inter-sublevel relaxations occurring in the larger QD. Here ηin denotes the transmission efficiency at the input interface, that is, the efficiency of the conversion from the optical far-field to the optical near-field at the input. The input signal is then transferred to a nanophotonic logic gate (e.g., NOT gate), which consists of one smaller and one larger QD, as shown in the middle of Fig. 1(b). The output optical near-field is scattered by a metal nanoparticle located in the vicinity of the quantum dot, is converted to an optical far-field, and is captured by a photodetector, as depicted in the right hand side of Fig. 1(b). Here, the output conversion efficiency from the optical near-field to the optical far-field is denoted by ηout, which is analyzed in detail later below. Also, we need to take into account the number of photons per time slot arriving at the photodetector, denoted by np, which should yield sufficiently low error rate in the photodetection. The operating speed of the total system depends on the architecture of the system, as discussed at the end of this letter.
We evaluate each of the parameters based on theoretical and experimental data. The architecture discussed in Fig. 1(b) will be experimentally fabricated as shown in Fig. 1(c), which is based on the technology of stacked quantum dots in which energy transfer occurs from smaller QDs to larger ones.\(^5\)

**[Input interface]** The energy dissipation associated with the input interface is given by \(\eta_{\text{in}} = 1 - \varepsilon_{\text{in}}\) where \(\varepsilon_{\text{in}}\) is the overall inter-sublevel relaxation occurring in the optical excitation transfer via optical near-field interactions. As discussed above, the transfer efficiency is high, similarly to light harvesting antennae in nature. Here, we assume that \(\varepsilon_{\text{in}} < 0.1\), meaning that \(\eta_{\text{in}}\) is greater than 0.9.

**[Logic gate]** The energy dissipation associated with the logic gate based on energy transfer via the near-field interaction is the inter-sublevel energy dissipation, whose lower bound is theoretically derived to be \(E_{\text{diss}} = 25\,\mu\text{eV}\) (Ref. 1) and experimentally estimated to be \(E_{\text{diss}} = 65\,\text{meV}\) in the case of a nanophotonic NOT gate based on two layers of InAs QDs.\(^5\)

**[Output interface]** The efficiency of the output interface is estimated based on experimental data in two layers of InAs QDs working as a NOT gate.\(^5\) It is evaluated by the following three steps. In the two layers of QDs, the size of the QDs in the first layer is smaller than those in the second layer, which is achieved by optimizing the parameters in the molecular beam epitaxy (MBE) process used to fabricate them.\(^5\) First, consider the system shown in Fig. 2(a), where InAs QDs are encapsulated in GaAs barrier layers. Let the radiation from the output QD (QD\(_2\)) in this setup be given by \(P_{\text{emit}}\). Due to Fresnel refraction, the ratio of the optical power extracted from the QD, \(P_{\text{extract}}\), is given by \(P_{\text{extract}}/P_{\text{emit}} = [(n_G - 1)/(n_G + 1)]^2\), where \(n_G\) is the refractive index of GaAs. Second, as shown in Fig. 2(b), the device is fabricated in a mesa structure. We experimentally evaluated that the optical power from the mesa device, \(P_{\text{mesa}}\), is half of that in the system shown in Fig. 2(a); that is, \(P_{\text{mesa}}/P_{\text{extract}} = 0.5\). Third, by placing a metal nanoparticle on top of the mesa structure (Fig. 2(c)), whose emitted optical power is denoted by \(P_{\text{np}}\), we can expect enhanced light scattering compared with the system shown in Fig. 2(b). Figure 2(d) shows a cross-sectional image of the system shown in Fig. 2(d) taken by a scanning transmission electron microscope.\(^5\) The interactions between semiconductor QDs and metal nanostructures have been studied in depth,\(^9\) but they have still not been clearly understood, particularly regarding the upper bound of the enhancement; for instance, a more than fivefold increase, as well as quenching in certain conditions, has been observed in CdSe/ZnS nanocrystals on metal surfaces by various groups,\(^10\) while modest increases have been reported in InGaAs QD/metal composites.\(^13\) In Ref. 5, thanks to the placement of an Au nanoparticle, the enhancement factor was experimentally estimated at 3. Based on this experimental value, which we also consider modest, in this letter we assume \(P_{\text{np}}/P_{\text{mesa}} = 3.0\). Summing up, the output interface efficiency is given by

\[
\eta_{\text{out}} = \frac{P_{\text{np}}/P_{\text{mesa}}}{P_{\text{mesa}}/P_{\text{extract}}} \times \frac{P_{\text{extract}}}{P_{\text{emit}}},
\]

which yields 0.45 based on the numerical values evaluated in the three steps discussed above.

We assume that 100 photons (\(n_p = 100\)) are required in order to obtain an error rate of \(10^{-9}\), assuming that an optical preamplifier is employed,\(^14\) which we consider one realistic operation. Thus, the energy required for the detector, denoted by \(E_{\text{det}}\), is given by \(E_{\text{det}} = n_p \hbar \nu\), where \(\nu\) is the optical frequency of the output beam and \(\hbar\) is Planck’s constant. Taking into account the efficiencies at the input, internal, and output stages, the required optical input energy, \(E_{\text{in}}\), is given by \(E_{\text{in}} = n_p (\hbar \nu + E_2)/(\eta_{\text{in}} \eta_{\text{out}})\), which was estimated to be 235 eV (theoretical) and 251 eV (experimental, wavelength 1.3 \(\mu\text{m}\)). Therefore, the total energy dissipation in the system is given by \(E_{\text{d,total}} = E_{\text{in}} - E_{\text{det}}\), which is 140 eV (22.4 aJ) (theoretical) and 156 eV (25 aJ) (experimental). Figure 3(a)
represents the breakdown of energy dissipation. We can find that the energy dissipation is dominated by the output interface, whereas that for the input interface, which is given by \( \varepsilon_d E_{\text{in}} \), is small, and that for energy transfer, given by \( n_p E_g \eta_{\text{in}} \eta_{\text{out}} \), is nearly negligible. This indicates that developing an improved output interface would significantly improve the energy efficiency. The energy dissipation of electronic wired devices, including interfacing, is estimated to be 6.3 MeV, indicating that the energy dissipation of nanophotonic devices is about \( 10^4 \) times more energy-efficient than their electrical counterparts (Fig. 3(b)).

The operating speed of the total system depends on the architecture of the device. First, suppose that there is one logic gate in the system, as shown in Fig. 1(b) and at the upper left in Fig. 3(c). Since the energy transfer time from the smaller dot to the large one is estimated to be \( \tau = 50 \text{ ps} \), the minimum duration of the time slot required to determine a single bit, requiring 100 photons (\( n_p = 100 \)), i.e., \( n_p E_g \eta_{\text{in}} \eta_{\text{out}} \) excitons passing the device, is given by \( n_p \tau / \eta_{\text{out}} \), which is about \( 17 \text{ ns} \), corresponding to a total system operating frequency of about 60 MHz. However, when we assume multiple identical devices operating in parallel or device redundancy, as schematically shown at the upper right in Fig. 3(c), the minimum duration for a single information bit could be shortened, enabling a higher operating speed. The tradeoff between such device redundancy and operating speed was also evaluated when \( n_p = 21 \), which is the quantum limit of detection yielding an error rate of \( 10^{-9} \), providing higher operating speed with the same parallelism compared with \( n_p = 100 \).

Finally, we make a few additional remarks. First, assuming electrical circuits with 30 nm feature size gives subpicosecond gate time and a dissipated switching energy of \( \sim 50 \text{ aJ} \). The comparison above considers energy dissipation including interfacing, which leads to \( 10^5 \) times higher energy efficiency with optical energy transfer. Superficially, however, the 50 aJ switching energy in electronics and the total energy dissipation for optical energy transfer in logic gates are comparable.

Second, when we consider multiple-input devices based on optical energy transfer, for instance, NOT gates or AND gates as in Ref. 5, we make use of energy resonance or off-resonance between quantum dots or state filling effects induced at larger quantum dots. It should be noted that the near-field–mediated optical energy transfer logic demonstrated in Ref. 5 and references therein is quite different in concept from other attempts in the field. In particular, it should be noted that additional input light, denoted by \( E_a \), is needed for inducing energy-resonance in implementing a NOT gate, for example, leading to additional input energy, but this does result in negligible energy dissipation (\( \varepsilon_d \times E_a \)) or heat generation within the device; namely, almost all of the energy is dissipated from the device under study as photon radiation. This is another unique mechanism inherent in logic based on optical energy transfer, in contrast to electronic devices, where the energy contributes to heat generation, which is the most severe issue in state-of-the-art electronics.

One final remark is that system architectures and applications based on optical energy transfer could be very different from those based solely on silicon electronics. For example, the parallel and autonomous features of optical energy transfer and optical interfaces with the real-world, including light energy inputs (wireless connections to power supplies) and sensors, would provide unique architectures and applications for nanophotonic devices and systems.

In summary, we theoretically and experimentally analyzed the energy dissipation in energy transfer mediated by optical near-field interactions and their interfaces with optical far-fields. Our findings provide insights that will aid in the further development of nanophotonic devices and systems.

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\[ \text{FIG. 3. (a) Energy dissipation breakdown. (b) Comparison of energy dissipation. (c) Evaluation of possible operating speed of the system based on the spatial parallelism of the internal logic gates, or device redundancy, and the number of photons/bit.} \]


