Long-Distance Resonant Energy Transfer Mediated by Hybrid Plasmonic–Photonic Modes

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ABSTRACT: Metallic nanostructures are well known for their potential to enhance resonant energy transfer between chromophores, mediated by their plasmonic field. In most cases, the distances for efficient energy transfer are determined by the dimensions of the structure, making dissipation in the metal dominant when long-range energy transfer is desired. Here, we propose and study a new mechanism for long-distance energy transfer, which can lead to highly efficient energy transfer over distances comparable to the optical wavelength, based on hybrid photonic–plasmonic modes in metallic structures. We study such structures theoretically and characterize the energy-transfer processes in them, showing that within these structures, energy can be funneled with ~25% efficiency over a range of about 150 nm, with minimal dependence on the location of the acceptor molecules inside the structure. Finally, we demonstrate this new mechanism experimentally, providing a proof-of-concept for long-distance energy transfer in such structures. Our multilayer system is compatible with standard photovoltaic and organic light-emitting diodes and therefore the mechanism presented can be readily employed in such organic optoelectronic devices to improve their performance.

INTRODUCTION

The potential for metallic nanostructures to improve energy transfer between chromophores has long been recognized. Since this early work, many different geometries have been proposed and studied, relying on either surface plasmons in planar structures or localized plasmons on metallic nanostructures to mediate long-range energy transfer. Motivated by the promising opportunities for solar energy, light-emitting devices, and other applications, enhancing the energy-transfer range and its efficiency using plasmonic systems is still a highly desirable goal, attracting considerable effort even today. In plasmon-mediated energy transfer, the excitation energy of an emitter is coupled to the confined mode of a resonant plasmonic structure, causing a significant enhancement of the near field generated by the donor. Moreover, the spatial extent of the field generated by the donor is then determined by the plasmonic structure, providing a mechanism for overcoming the short-range nature (with a 1/R⁶ distance dependence) of the usual Förster resonance energy transfer (FRET) process. Indeed, using plasmonic structures, energy transfer over distances 1–2 orders of magnitude larger than the nanometric scale typical of FRET has been reported. However, since the length scale for efficient energy transfer is usually set by the dimensions of the structure, carrying the energy over long distances requires larger structures, which unavoidably makes the losses in the metal dominant and limits the energy-transfer efficiency. Recently, strong light-molecule coupling has been demonstrated to provide an alternative route for enhanced energy transfer, taking advantage of the collective nature of resulting polaritonic states. However, reaching the strong coupling regime in such systems typically requires high molecular densities, which is not always permissible in practical applications.

Here, we explore a new mechanism for long-range energy transfer between chromophores, using a metal-dielectric microcavity and strong coupling between surface plasmons and cavity photons. Taking advantage of the delocalized nature of the hybrid photonic–plasmonic modes, we achieve energy transfer with an efficiency of ~25% over distances of 100–200 nm. Moreover, we show that the spectral response of the structure and the wavelength dependence of the energy-transfer efficiency can be conveniently tailored. This property provides superior flexibility in the selection of the donor–acceptor pair compared to previous methods.

HYBRID PLASMONIC–PHOTONIC MODES IN A METALLIC MICROCAVITY

In their pioneering work, Andrew and Barnes showed that normal-mode coupling between two surface plasmons residing on either side of a metal layer can be used for transferring energy from donor molecules deposited on one side to acceptor molecules on the opposite side. Using the coupled plasmonic modes as an “optical bridge” between the molecules, these experiments demonstrated energy transfer across metal...
films as thick as \( \sim 100 \) nm. In our work, we rely on a similar optical-mode coupling to mediate energy transfer between remote molecular layers. However, here, we strongly couple a surface plasmon mode with a microcavity mode, taking advantage of the properties of these two different electromagnetic excitations. On the one hand, the plasmonic mode acts as a very efficient channel to capture the donor emission due to its evanescent nature and the increased density of states in its vicinity.\(^{29}\) On the other hand, the cavity mode primarily resides in the dielectric medium within the cavity, minimizing losses in the metal. As we show, the mixing between these modes can provide a new mechanism for long-distance energy transfer, which maintains its high efficiency even over distances comparable to the optical wavelength.

As illustrated in Figure 1a, our system is a half-wavelength metallic Fabry–Pérot cavity consisting of two Ag mirrors separated by a \( \sim 160 \) nm thick dielectric layer (e.g., transparent polymer), taken with a refractive index of \( 1.5 \). In addition to the standing-wave mode residing between the cavity mirrors, this structure also supports surface plasmon modes at the top metal–air interface. By making the top silver mirror sufficiently thin (\( < 70 \) nm), we allow a small leakage of the plasmonic field through the metal film and into the cavity, where it overlaps with the intracavity photonic field. As a result, the plasmonic and photonic modes can interact resonantly, resulting in the formation of hybrid modes, which are linear combinations of the photonic and plasmonic modes.\(^{30}\) As we demonstrate here, these hybrid modes can mediate energy transfer between donor molecules placed on top of the structure and acceptor molecules residing inside the cavity region. In our calculations, we assume that the acceptor molecules are homogeneously and isotropically distributed in the cavity. Furthermore, the donor layer, which is assumed to be infinitely thin, is separated from the top Ag mirror by a thin (9 nm) polymer spacer to prevent dissipation into lossy surface waves.\(^{36,31}\)

The resonant plasmon–photonic coupling is demonstrated in Figure 1b, showing the simulated dispersion of the structure (energy vs in-plane momentum, \( k_x \)), as well as the dispersion curves of the uncoupled cavity photons (white solid line) and surface plasmons at the metal–air interface (white dashed line). The dispersion was obtained by calculating the reflectivity of the structure, which was carried out using the transfer-matrix formalism,\(^{32}\) and expressing the Fresnel coefficient in terms of the in-plane momentum. As seen, at the crossing point of the cavity and the plasmon lines, the dispersion of the composite structure splits into two branches, which are separated by a distinct energy gap. This splitting signifies the resonant coupling between the two electromagnetic modes, and the energy gap corresponds to the coupling strength, which is determined by the thickness of the top mirror. As shown in Figure 1c, the mixing between the photonic and plasmonic modes varies with the in-plane momentum, giving rise to different spatial distributions of the electromagnetic field for different locations on the dispersion curve. Far from resonance, the electric field shows the characteristics of a standing-wave mode (Figure 1c,i) or an evanescent plasmonic mode (Figure 1c,ii). However, around the resonance, the modes are a symmetric (Figure 1c,iii) and an antisymmetric (Figure 1c,iv) combination of the plasmon and the cavity modes, exhibiting both exponential decay into air and a standing-wave pattern in the dielectric layer between the mirrors. For the specific choice of parameters for the structure, the wavelengths of these mixed modes are 575 and 535 nm. This normal-mode splitting is similar to the splitting occurring for surface plasmons in thin metal films\(^{3,33,34}\) or localized plasmons in nanoparticles.\(^{35,36}\) However, here, we couple electromagnetic modes with different natures, giving rise to hybrid photonic–plasmonic modes. These modes, which reside both outside and inside the metallic cavity, can be used to efficiently funnel energy from a donor overlayer located above the top mirror to acceptor molecules located deep within the cavity region. The precise location of the resonance can be controlled by varying the distance between the cavity mirrors. Moreover, since the plasmon–photonic coupling is determined by the leakage of the plasmonic tail into the cavity and its modal overlap with the cavity mode, we can easily control the coupling strength and the spectral splitting in the dispersion by changing the thickness of the Ag mirror. These properties make this structure very versatile, as the energies of the coupled modes can be conveniently tuned to match the spectra of a desired donor–acceptor pair. We note
that the observed line-crossing and normal-mode splitting are possible only due to the higher refractive index of the medium inside the cavity (compared to air on the plasmon side), which allows the cavity dispersion to extend beyond the air light line and to cross the plasmon dispersion.

SIMULATIONS OF ENERGY TRANSFER IN METAL-DIELECTRIC CAVITIES

A convenient theoretical approach for studying energy transport in photonic structures is the widely used dyadic Green’s function formalism.\(^{37–40}\) To study the energy transfer in our structures, we follow Celebi et al.,\(^{3}\) who showed that, for a layered system, simple expressions for the energy-transfer efficiency can be obtained from the dyadic Green’s function. We characterize each layer \(j\) with a homogeneous and isotropic dielectric function \(\epsilon_i = \epsilon_0\) (with \(\epsilon_0\) the dielectric constant of vacuum) and define the normalized in-plane moment as \(\epsilon_j = k_j = \frac{\omega}{c}\) with \(k_j = \sqrt{\epsilon_j}\) being the wavenumber in the vicinity of the donor, where \(\omega\) is the donor oscillation frequency and \(c\) is the speed of light in vacuum. Furthermore, for each layer, we define the normalized longitudinal wavenumber as \(h_j = k_j = \frac{\sqrt{c}}{\sqrt{\epsilon_j}}\). Using these definitions, the total flux through a horizontal plane at a height \(z\) can be calculated using the normal component of the Poynting vector \(S\), giving

\[
\text{Re} \int S^\perp dA = \int_0^\infty \frac{3q}{4} \text{Re}\left\{ \frac{u'(\sqrt{\epsilon_j})^h}{h^j} [F^p(z) - B^p(z)] \right\} du
\]

for a vertical dipole and

\[
\text{Re} \int S^\parallel dA = \int_0^\infty \frac{3q}{8} \text{Re}\left\{ \frac{u'(\sqrt{\epsilon_j})^h}{\sqrt{\epsilon_j}} [F^p(z) - B^p(z)] \right\} du
\]

for a horizontal dipole. Here, \(q\) is the emission quantum yield of the donor and \(F^\parallel(z) = B^\parallel(z)\) describe forward- and backward-propagating plane waves for \(p\) and \(s\) polarizations, respectively. Within the \(j\)th layer, these fields can be written as

\[
F^\parallel(z) = e^{i\omega z/c} e^{i\delta h_j(z - z_j)}
\]

and

\[
B^\parallel(z) = e^{i\omega z/c} e^{-i\delta h_j(z - z_j)}
\]

where \(\delta\) represents the location of the top interface of each layer and the field amplitudes \(F^\parallel(z)\) and \(B^\parallel(z)\) are related by the Fresnel coefficients for transmission and reflection between adjacent layers, respectively. For the case in which the donor is located just above the structure (taken as \(z = 0\)), we numerically calculate these amplitudes for each value of \(u\) taking \(f^{\parallel\parallel} = 1\) and \(h^{\parallel\parallel} = 0\). Once the energy flux in each plane is known, the fraction of donor energy dissipated in the \(j\)th layer is then calculated by taking the difference in the net flux going through the bottom and top interfaces of the layer and then normalizing by the enhancement factor of the donor decay rate (due to the modified local density of states near the structure), which is given by

\[
f^j = 1 + \frac{3q}{2} \text{Re} \int_0^\infty \frac{u^3}{h^j} du
\]

for a vertical dipole and

\[
f^j = 1 - \frac{3q}{4} \text{Re} \int_0^\infty \frac{u}{h^j} (r^h d_j - r^j) du
\]

with \(r^h = b^h_j\) and \(r^j = b^j_j\) being the reflection coefficients of the complete structure, for light coming from the donor side.\(^{1–4}\) can be used to calculate the yield of energy transfer from the donor to the whole acceptor layer under the assumption that the acceptor molecules are isotropically and homogeneously distributed within the host layer and can thus be described by a complex dielectric function \(\epsilon_i(\omega)\). Moreover, by taking the real part of the integrands in eqs 1 and 2, calculating the derivatives with respect to \(z\) and normalizing by \(F^\parallel/2\), we obtain the distribution of energy transfer \(\phi(k_a, z)\). This quantity describes the efficiency (fraction of the donor energy) at which energy is transferred through modes with a particular in-plane momentum value \(k_a\) and dissipated at height \(z\) within the structure.\(^4\) Generally, it is possible to represent the energy-transfer efficiency as a spectral integral over a product of three components, which are the (normalized) fluorescence spectrum of the donor; the absorption cross section of the acceptor; and a coupling factor, which describes the effect of the structure and generally may depend on the intermolecular distance, molecular orientation, and wavelength.\(^23\) To understand the contribution of the hybrid plasmonic–photonic modes to the energy-transfer process, we focus here on the structural coupling factor. Therefore, in the following, we will assume a wavelength-independent emission for the donor and use a constant imaginary part for the refractive index in the acceptor layer, taken here as \(\text{Im}\{\sqrt{\epsilon_i}\} = 0.025\) (which is the highest absorption of the host/acceptor layer, which does not affect the dispersion of the structure).

Figure 2 shows the energy-transfer distribution \(\phi(k_a, z)\) (logarithmic scale) in the vicinity of the hybrid plasmonic–photonic modes (points (iii) and (iv) in Figure 1b) corresponding to the wavelengths 535 and 575 nm) for a vertical dipole (Figure 2a,c) and for a horizontal dipole (Figure 2b,d). As can be seen, the energy dissipation occurs both in the metal mirrors and in the acceptor layer, and it is concentrated around several distinct values of the in-plane momentum \(k_a\), as expected for a system having a resonant response. In all four cases, the most dominant channel for energy dissipation in the acceptor layer resides around \(k_a = 12.2\ \mu\text{m}^{-1}\), corresponding to the avoided crossing point on the dispersion curve. This result clearly demonstrates that the coupling between the plasmonic and photonic cavity modes can indeed induce an efficient channel for energy transfer between the donor and the acceptor within the cavity. In addition to this channel, we also observe several other and less efficient channels for energy transfer. For 535 nm (Figure 2a,b), a weaker peak can be seen at \(k_a ∼ 15\ \mu\text{m}^{-1}\), originating from a mode that is primarily concentrated in the cavity, as it resides in a photonic-like region of the dispersion curve (see Figure 1b). Furthermore, we also observed a small contribution from plasmonic modes at higher values of \(k_a\) which lie beyond the light line of the host polymer (having a refractive index of 1.5) and correspond to surface plasmon modes at the Ag–polymer interfaces. All of
these energy-transfer paths are similarly seen in the case of a horizontal donor (Figure 2b,d), but here, their magnitudes are lower. In addition, the horizontal donor also transmits some of its energy through low $k$$_z$ modes, which have a predominantly photonic-like nature. Interestingly, in comparison to all other channels, for the hybrid modes, the dissipated power density inside the acceptor layer hardly shows any variation with height, meaning that the energy-transfer efficiency in these structures is practically independent of the location of the acceptor molecule within the cavity. This unique behavior is distinctively different from the usual behavior seen in Förster-type energy transfer, which decreases as the sixth power of the distance, or plasmon-mediated energy transfer, which decays exponentially with distance. To highlight the effect of this behavior, we calculate the energy-transfer efficiency profile across the structure, which represents the fraction of the donor energy (at a given wavelength) that is transferred to structure at a given height $z$. This profile is calculated by numerically integrating the energy-transfer distribution $\phi(k_x, z)$ (Figure 2a,c) over the in-plane momentum. The results (for a vertical donor) are shown in Figure 3a for 535 nm and in Figure 3b for 575 nm, where the solid lines correspond to a full integration over all $k_x$ values and the dashed line is the result of the integration over a narrow region around $k_x \sim 12.2 \mu$m$^{-1}$, which takes into account the contribution of the hybrid modes only. In both cases, we observe narrow and exponentially decaying peaks in the metal mirrors, whereas the energy-transfer profile within the acceptor layer is almost flat, with only weak spatial variations coming from the nonhybrid modes. These results also show that energy transfer occurs predominantly through the hybrid modes (dashed lines in Figure 3a,b), which is responsible for 60–80% of the donor–acceptor energy-transfer yield. The invariance of the energy-transfer profile within the cavity may seem counterintuitive at first, but it can be understood in the following way: For surface plasmons at the metal–air interface, the field transmitted into the polymer propagates at an angle very close to 45° (with in-plane momentum just outside the air light line). In the cavity region, this field is composed of two counterpropagating planewaves of similar amplitudes, which are given by $F(z) \sim e^{ik_xz}$ and $B(z) \sim e^{-ik_xz}$. At each point, the energy absorbed by the acceptor will be proportional to the local intensity, which is taken as $|E_x|^2 + |E_y|^2$, with $E_x(E_y)$ being the in-plane (normal) component of the electric field. For p-polarization and a propagation angle of 45°, these projections are given approximately as $E_x \sim e^{i\pi z/L} - e^{-i\pi z/L} \sim \sin \frac{\pi z}{L}$ and $E_z \sim e^{i\pi z/L} + e^{-i\pi z/L} \sim \cos \frac{\pi z}{L}$ (where we have used the cavity resonance condition given by $2k_xh_L = 2\pi$, i.e., constructive interference for a complete round-trip, with $L$ being the cavity thickness). Therefore, the sum of their absolute square values is constant, resulting in a nearly uniform absorption profile for the acceptors inside the cavity. In Figure 3c,d we plot the exact distributions of $|E_x|^2$ (blue line) and $|E_y|^2$.
(red line) components for the symmetric (Figure 3c) and antisymmetric (Figure 3d) hybrid modes, as obtained from the numerical simulations. As can be seen, the field intensity profiles indeed match our qualitative description above. This result also implies that if the acceptor molecules are concentrated in a thin layer inside the cavity (rather than homogeneously distributed over the entire cavity region), similar energy-transfer efficiency will be obtained, irrespective of the location of the layer within the cavity and its distance from the donor layer.

To fully characterize the different energy-transfer pathways to the acceptor, we integrated the energy-transfer distribution (see Figure 2) over the entire height of the acceptor layer, which gives the total energy dissipation in the acceptor layer as a function of in-plane momentum. We repeated the calculation for a series of wavelengths in the range of 400–800 nm, and the results are shown in Figure 4a,b, for a vertical and horizontal donor, respectively. When displaying the energy-transfer efficiency as a function of emission wavelength, one can see that modes throughout the whole dispersion contribute to the donor–acceptor coupling process, but the most dominant contribution comes from the region around the crossing point between the plasmon and cavity dispersion lines, confirming that the mixing between these modes is the dominant channel for energy transfer in our system. One can also note the two weaker curves lying beyond the light line of the polymer (marked by the white dashed lines), which are attributed to surface plasmon modes residing on the interfaces between the metal mirrors and the high-refractive-index layers.

Finally, we calculate the total energy-transfer efficiency, given by \( \int \phi dk \), where the integration is carried out over the entire acceptor layer and over the entire \( k_x \) axis. We plot the results as a function of wavelength in Figure 4c for a vertical dipole (blue curve) and for a horizontal dipole (red curve). The two spectra exhibit broad distributions, with maxima close to the hybrid mode wavelengths. Specifically, for the vertical dipole, the spectrum is composed of two, partially overlapping contributions: one at the higher-energy coupled mode (535 nm) and a slightly weaker one at the lower-energy coupled mode (575 nm). The higher-energy-transfer efficiency of the high-energy mode could be related to its asymmetric spatial distribution (see Figure 1c,iii), which leads to a smaller fraction of energy being absorbed by the metal mirror, as can also be seen when comparing the energy-dissipation distributions in Figure 2a,c for these two wavelengths. Most importantly, the results show that the hybrid plasmonic–photonic structure leads to a donor–acceptor coupling efficiency larger than 20% over separation distances in the range of 100–200 nm.

To assess the contribution of the resonant plasmon–photon coupling, we remove the bottom mirror such that the cavity mode does not exist and energy transfer can only occur through the plasmonic modes residing on both sides of the top Ag mirror. This configuration is similar to the one studied in ref 3; however, due to the asymmetry between the upper and lower sides of the mirror, the coupling between the two plasmonic modes is very weak. Figure 5a shows the calculated energy-transfer distribution for this structure, with a vertical donor emitting at 535 nm. As can be seen, the energy transfer can still occur across the metal film via these plasmonic modes; however, in comparison to Figure 2a, we find that a much larger fraction of the energy is dissipated in the metal layer, primarily in the plasmonic mode at the metal–air interface. When integrating over the whole in-plane momentum axis and over the entire acceptor layer, we find that the total energy-transfer efficiency is around 6%, which is about 4 times smaller than in the hybrid plasmonic–photonic structure. Next, we...
repeat the same calculations with both Ag layers removed. In these calculations, we keep the distance between the donor and acceptor layers fixed (i.e., 52 nm) and replace the top Ag mirror by a poly(vinyl alcohol) (PVA) spacer. Since this distance is much larger than the FRET radius and the plasmon-mediated energy transfer is absent, energy transfer can only occur through a trivial radiative process. As seen in Figure 5b, this radiative energy transfer is uniformly distributed within the region between the air light line and the glass light line, corresponding to free photons propagating at angles of 42°–90° through the polymer–acceptor layer. In this configuration, we find that the fraction of the donor energy absorbed by the acceptor molecules is around 15%. Therefore, we conclude that even though the incorporation of metal in our plasmonic–photic system inevitably introduces losses, its effect on the energy flow between the donor and acceptor still results in higher energy-transfer efficiency, and that this enhancement is due to the resonant coupling between the plasmonic and photonic modes.

**EXPERIMENTAL METHODS AND RESULTS**

To demonstrate the long-distance energy transfer in the hybrid cavity, we fabricated three types of cavity samples: one with both the donor and acceptor molecules, and two reference samples with either the donor alone or the acceptor alone. We chose to work with fluorescein as the donor molecule and rhodamine B (RhB) as the acceptor molecule. The micro-cavities were prepared by sputtering a thin (35 nm) silver layer onto a glass substrate, followed by the deposition of a 164 nm layer of poly(vinyl alcohol) (PVA, MW 205 000; Sigma-Aldrich). This layer was deposited by spin-coating a 3 wt% PVA/H2O solution at 1800 rpm. For the samples containing the acceptor molecules, the polymer was doped with rhodamine B molecules (RhB, Sigma-Aldrich), which were added to the PVA solution before spin-coating in a 1:4700 mass ratio. Next, a second silver layer (43 nm thick) was sputtered on top of the polymer to complete the cavity and covered with a very thin PVA spacer (~9 nm). The same spacer was deposited above all of the samples to avoid any differences in the dispersion of the three samples. Finally, for the samples containing the donor molecules, we deposited the fluorescein molecules (Sigma-Aldrich) by spin-casting a 2.7 × 10−7 M fluorescein/EtOH solution at 1000 rpm. In our experiments, we used low dye concentrations for both the donor and acceptor, to avoid strong light-molecule coupling and its contribution to the energy-transfer process.

Figure 6a shows the excitation (dashed lines) and emission (solid lines) spectra for fluorescein (in blue) and RhB (red), measured using a HORIBA Jobin Yvon Fluolog FL-3 spectrofluorometer. As seen in Figure 6a, the fluorescein excitation and emission peaks are around 503 and 523 nm, respectively, whereas the rhodamine B (RhB) has an excitation peak at 555 nm and an emission peak at 577 nm. Next, we used a dedicated single-shot Fourier plane imaging system to measure the angle-resolved reflection spectroscopy. The white dotted lines show the simulated dispersion calculated for the same structure. The horizontal white lines correspond to the emission peak of fluorescein (solid line) and the excitation peak of RhB (dashed line). Emission (c) and excitation (d) measurements performed on the samples containing donor molecules (blue curve), acceptor molecules (red curve), and both donor and acceptor molecules (black curve).

![Figure 6](image-url) - (a) Excitation (dashed lines) and emission (solid lines) spectra measured for fluorescein (blue) and RhB (red) molecules. (b) Dispersion diagram of the fabricated sample, measured by angle-resolved reflection spectroscopy. The white dotted lines show the simulated dispersion calculated for the same structure. The horizontal white lines correspond to the emission peak of fluorescein (solid line) and the excitation peak of RhB (dashed line), ensuring efficient coupling of the molecules to the hybrid modes. We verified that the two other samples (i.e., containing either the donor or the acceptor alone) have the same characteristic dispersion (up to deviations of 30 meV, which is smaller than half-width at half-maximum of the absorption spectrum of the molecules, being ~70 meV).

Finally, we proceeded to characterize the photoluminescence properties of the samples. The emission is collected from the cavity samples at 45°, whereas the excitation beam is launched at 62.5° (with respect to the cavity normal). As shown in Figure 6c,d, we performed measurements comparing the donor/acceptor sample (D + A) and the reference samples with donor alone (D) and acceptor alone (A). When exciting the sample containing the acceptor alone (red curve) at 470 nm, we observe an emission peak around 540–550 nm. We note that this emission is slightly blue-shifted with respect to the emission of the bare molecular film molecules, which results from the different optical environment and the angle-dependent out-coupling for the emission when exiting the cavity. This emission peak is not observed for the sample containing the donor alone (blue curve). In the mixed sample (black curve), we find a pronounced 3- to 4-fold emission enhancement, suggesting increased efficiency of energy transfer.
energy transfer over a distance of that the hybrid plasmon reference samples (acceptor or donor alone; red and blue nm). This excitation peak does not appear in any of the reference samples (acceptor or donor alone; red and blue curves, respectively), indicating that this signal is indeed triggered by absorption into the donor molecules, which subsequently transfers their excitation energy to the acceptor molecules. Therefore, our result provides a proof-of-concept that the hybrid plasmon—photonic cavity can indeed mediate energy transfer over a distance of ~150 nm, as predicted by our simulations.

CONCLUSIONS

In summary, we studied energy transfer in hybrid structures supporting both photonic cavity modes and surface plasmon modes, both theoretically and experimentally. We showed that with an appropriate design these two different types of waves can strongly couple to form composite modes, which simultaneously extend over the interior part of the structure as well its outer side. Most importantly, we demonstrated that these mixed modes can give rise to a new energy-transfer mechanism and efficiently mediate energy transfer over large distances. In a manner similar to earlier research, which harnessed the plasmonic modes of metallic structures, our mechanism gives rise to nonradiative energy transfer over distances much larger than the typical FRET radius and comparable to the optical wavelength. However, since our method relies on the coupling between surface plasmons and photonic modes, the length scale for energy transfer is no longer set by the dimensions of the metallic part of the system. Therefore, the amount of metal can be significantly reduced, which lowers parasitic losses in the metal and increases the overall energy-transfer efficiency. Our simulations show that the coupling efficiency provided by the structure is around 20–25%, and further study is required to understand the influence of the structure parameters on the energy-transfer process and to optimize it, potentially obtaining even higher coupling efficiencies. Another advantage of our new mechanism is that the spectral properties of the structure can be easily tuned to match a large variety of different donor—acceptor pairs. The planar architecture of the hybrid structure naturally lends itself to different organic electronic devices and may prove to be beneficial in light-harvesting applications, in which solar energy needs to be absorbed and then efficiently transported into the active region inside the device, where it is converted to electrical energy.

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Notes

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