Controllable Excitation of Surface Plasmon Polaritons in Graphene-Based Semiconductor Quantum Dot Waveguides

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The research aim of this study is the development of a theoretical semiclassical model of the controllable excitation and propagation of surface plasmon polaritons (SPPs) in planar graphene waveguides by the application of external voltage. The model is based on the numerical solution of the SPP's dispersion equation formulated for a system including two coupled graphene sheets with embedded quantum dots. Using the developed model, the different near-field patterns realized in the waveguides depending on the quantum dots’ ordering and an external voltage applied independently to each graphene sheet with additional gold electrodes are numerically investigated. The obtained results show that the application of external voltage can locally change the chemical potential of graphene and, thereby, lead to controllable excitation of SPPs in the corresponding graphene waveguide. Furthermore, we revealed that the propagation direction of the excited SPPs is determined by the geometrical configurations of the gold electrodes that provide the required SPP routing. The investigated system offers new opportunities for near-field energy transport and concentration, which can be applied to develop ultra-compact photonic devices.

1. Introduction

The realization of light control on the nanoscale is a fundamental problem of modern nano-photonics and plasmonics. In this context, all-graphene-based technologies seem to be suitable approaches for solving the problem since the electromagnetic field is well-localized on graphene,[2,3] whereas the quantum dots (QDs) can be highly efficient converters of light into the near-field[4] in the wide spectral range. At the same time, the questions of the experimental development of graphene systems with the required properties and the creation of appropriate interfaces have been opened so far.

When the circuit’s speed is not a priority, simple voltage control can be used to manipulate the localized field states on graphene.[5–9] In its pristine condition, graphene has a vanishing density of states at the Fermi level, which is not good for superconductivity. Still, if it can be heavily electron-doped, it is predicted to become a superconductor.[10] The conventional commercial graphene has the chemical potential $\mu$ of about 0.1 eV, and for doped graphene, it can reach values of up to 0.6 eV,[11] but these values are fixed. The main effect for controlling the chemical potential is the dependence of the graphene carrier density on the external voltage (or electric field strength).[11–13] The theory for voltage control of the electrochemical potential of graphene is presented in ref. [12, 14]. The possibility of the local voltage control of the electrochemical potential for guiding of surface plasmon polariton (SPP) waves was considered in refs. [11, 13]. For example, when a positive potential is applied to the ribbon-like control electrode, the local density of charge carriers and electrochemical potential of graphene against the ribbon-like section increases.[11] The pump frequency and voltage are tuned in such a way that graphene near the ribbon behaves as a metal with a positive imaginary part of conductivity and can support SPP waves. In the region outside the ribbon-like section, the field attenuates, and the electrochemical potential decreases so much that the imaginary part of graphene conductivity becomes negative, and graphene does not support SPP. In general, varying the geometry of the control electrode allows to create waveguide areas in graphene between two boundaries, where the type of graphene conductivity changes.[11]

The excitation of SPPs on graphene requires the use of either time-tested technologies[15] or more lab-consuming approaches that promise much higher light-SPP conversion coefficients. In the latter case, this approach can be associated with the use of classical optical resonances[16–19] and new quantum-configuration resonances[4,20] with nanostructures and quantum dots (QDs) located near the interface of two materials or embedded into the medium with spatial constraints. In such schemes, the QDs pumped by an external source can exchange the energy with quasiparticles formed in the system, including localized...
modes of photonic crystal,[21] SPPs,[20] and phonon–plasmon polaritons.[22] The remarkable feature of QDs is the ability to tune their photoluminescence frequencies to the desired spectral range by changing their shape and geometrical sizes.[23] At the same time, such a point emitter becomes an excellent source of near-field excitations when a suitable distance to the surface is chosen.[24,25] However, for efficient excitation of plasmon polaritons in graphene (under condition \( \hbar \omega < 2 \mu_c \), where \( \hbar \omega \) is the photon energy of the pump field), QD photoluminescence in the mid-wave infrared (MWIR, 3 – 6 \( \mu m \)) range is required, which significantly reduces the choice of semiconductors for their fabrication. Suitable semiconductor QDs must have a very small band gap for emitting such wavelengths on an interband transition or large values of scattering cross-sections on intraband transitions for the first levels of the conduction band.[26] In this sense, good candidates for SPP generation on planar or multilayer graphene sheets are HgTe QDs with bright photoluminescence in MWIR emitted by both intra- and interband transitions.[27,28] Other candidates are less toxic and more stable Ag\(_2\)Se QDs,[29,30] which produce power photoluminescence at a wavelength near 5 \( \mu m \).

Note that single QDs or their disordered arrays cannot provide sufficient efficiency of light-SPP conversion. Instead, cooperative phenomena and collective near-field effects[31] with highly localized states of the electromagnetic field can be used. Such effects are self-phasing in the form of superradiance[32] and localization due to defects.[33]

In the present paper, we focus on investigating optimal configurations of Ag\(_2\)Se QD arrays loaded into a graphene waveguide[34] to achieve a strong near-field due to QDs excitation by an external pumping wave. We also numerically study the possibility to control the subwavelength light energy concentration in graphene systems and advanced 2D materials[35] with QD structures by applying an external voltage. Such a combination of ordered nanostructures with an external modulation of their physical characteristics[36] (provided, for example, by an electric voltage) allows extending the ways to control the localization of light at the nanoscale. Similar approaches are already extensively used in plasmonics and nanophotonics to create bright light sources[37] dense coding of information,[38] and velocity light control.[39] Such systems can also include modern topological lasers based on the combination of a pair of resonant structures with considerably different geometries and different scales, which leads to the creation of high concentrations of optical energy.[40,41]

In our model, we consider a combination of two systems. The first is a graphene waveguide loaded with quantum dots. The second is a capacitor consisting of a gold stripe and a graphene sheet of the waveguide. The capacitor system is used for the realization of the local voltage control of graphene chemical potential \( \mu_c \). We investigate the possibility of satisfying the condition \( \hbar \omega < 2 \mu_c \) for the SPP excitation due to the relaxation of the excited QDs by applying an external voltage. Because the voltage will act locally, just below the gold stripe, the graphene SPPs can be excited only in this area. The QDs placed outside the area with \( \hbar \omega < 2 \mu_c \) are not coupled with the SPPs, and therefore, their relaxation occurs into light and phonons. The suggested system can provide controllable selective excitation and routing of the graphene SPPs. Note that the distances between individual QDs in the system are chosen to be the same order of magnitude or larger than the characteristic SPP wavelength in the system. Considerable reduction of such a distance can lead to an increase in the role of near-field dipole–dipole interaction (DDI) between nanoparticles (NPs)[42–44] and changing the regime from plasmonic waveguide to non-radiative energy transmission by means of photonic bound states.[45]

In our investigation, we use a semiclassical approach to define the graphene waveguide system’s main parameters with an Ag\(_2\)Se QD array that can lead to the excitation of graphene SPPs only in the local space between the gold stripes used to connect external electrical voltages. Using numerical simulation based on the finite difference time domain method, we reveal an unusual regime of a low-frequency modulation of the SPPs excited in the graphene waveguide by the SPPs excited on the gold stripes. Such structures with an SPP-SPP modulation can be suggested for the development of ultra-thin laser systems and all-graphene devices for controlling light at the nanoscale.

2. Model of SPP Generation and Voltage Control in the Two Graphene Sheets Plasmonic Waveguide Loaded with Ag\(_2\)Se Quantum Dots

The functional block for localization and routing of the near-field energy as a part of the general SPP circuit is shown in Figure 1. The graphene plasmonic waveguide composed of two graphene sheets is embedded in the silica host medium. Each graphene sheet is located on a buffer hexagonal boron nitride (hBN) layer with permittivity 3.6[6] and the gold stripes are deposited to the outer part of the circuit. Then, it is possible to apply a voltage between the selected stripes and the graphene to modify the graphene area’s chemical potential near the live stripe.

To characterize and demonstrate the basic functional features of the device presented in Figure 1, as a beginning, we consider several important elements of the system.

The graphene permittivity at the angular frequency \( \omega \) can be represented in the form:

\[
\varepsilon_\parallel = 1 + \frac{i \sigma}{\omega \Delta g \varepsilon_0}
\]  

(1)
where $\Delta_g$ is the thickness of the graphene in the surrounding medium with permittivity $\varepsilon_g$, $\varepsilon_0$ is the vacuum dielectric constant. The graphene conductivity can be described by the Kubo formula:\cite{46},

$$\sigma(\omega, \mu_c, \tau, T) = \frac{-i e^2 / \pi h^2}{\omega + i/\tau} \int_0^\infty e \left( \frac{\partial f_0(e)}{\partial e} - \frac{\partial f_0(-e)}{\partial e} \right) de$$

$$- \frac{i c^2(\omega + i/\tau) / \pi h^2}{(\omega + i/\tau)^2 - 4(e/h)^2} \int_0^\infty \frac{f_0(e) - f_0(-e)}{(\omega + i/\tau)^2 - 4(e/h)^2} de$$

(2)

where $1/\tau$ is the electron scattering rate, $f_0(e) = 1/(e^{(e-\mu_0)/kT} + 1)$ is the Fermi-Dirac function, $T$ is the temperature, $k$ is the Boltzmann constant, $\hbar \equiv \pi / h$ is the reduced Planck’s constant, $e$ is the electron charge, and $c$ is the speed of light in a vacuum. The first integral for the intraband $\sigma_{\text{intr}}$ and the second for the interband $\sigma_{\text{inter}}$ conductivity in (2) can be approximated in conditions $kT < |\mu_0|$ by $\hbar \omega$ as

$$\sigma_{\text{intr}}(\omega, \mu_c, \tau, T) = \frac{8e^2kT/h}{\omega + i/\tau} \left( \frac{\mu_c}{kT} + 2\ln \left( e^{\frac{\mu_c}{kT}} + 1 \right) \right)$$

(3a)

$$\sigma_{\text{inter}}(\omega, \mu_c, \tau, T) \approx \frac{i \sigma_0}{\pi} \ln \left( \frac{2\mu_c + (\omega + i/\tau)h}{2\mu_h + (\omega + i/\tau)h} \right)$$

(3b)

where $\sigma_0 = 4\pi e^2 / (2h)$. The frequency dependencies for the real and imaginary parts of the conductivity are shown in Figure 2a. Note that for terahertz, far- and mid-infrared (IR) radiations, the effect of the interband conductivity can be neglected\cite{47} for graphene with $\mu_c > 0.2$ eV.

The basic properties of single quantum dots synthesized from Ag$_2$Se QDs are presented in refs. [29, 30]. An important feature of Ag$_2$Se QDs is a very small band gap, which makes them attractive quantum objects for controlling the photoluminescence spectrum by changing their radius.\cite{48} Such dependence can be approximately described as follows:\cite{49}

$$\omega_{12} = \frac{eE_t}{h} + 2\hbar \varepsilon_0^2 + \frac{1}{m_c} + \frac{1}{m_h} - \frac{3.56 e^2}{\hbar \omega_{12} D_{QD} QD^2 4\pi E_0}$$

(4)

where $m_c = 0.32m_0$ and $m_h = 0.54m_0$ are the effective masses of the electron and the hole,\cite{29,30} respectively; $E_t = 0.07$ eV is the bulk band gap of Ag$_2$Se assigned to the tetragonal phase,\cite{29,51–53} $D_{QD}$ is the diameter of Ag$_2$Se QD, $\varepsilon_d$ is the static dielectric constant of Ag$_2$Se (we assume $\varepsilon_d = 11$\cite{54}). $\kappa_{10}$ is the root of the Bessel function, $\mu_c$ is the free electron mass, and $\mu_h$ is the electric constant.

Figure 2b shows the wavelength dependence of the interband $1S(\varepsilon) = 1S(\hbar)$ transition on Ag$_2$Se QD radius in MWIR. We assume that the QDs are pumped by a plane wave at a wavelength $\lambda = 4.5$ µm, which is normal to the graphene waveguide plane. Then, the relaxation of the excited QDs with a diameter $D_{QD} = 5.794$ nm in the proximity of the graphene sheet with a chemical potential $\mu_c = 0.3$ eV leads to the effective excitation of the graphene SPPs. It is possible because the wavelength of the interband transition for such QDs is $\lambda_{0d} = 5.864$ µm (see Figure 2b), and then the real part of the graphene permittivity takes a negative value, that is, $\varepsilon_{0d} = 1 - \frac{\mu_c}{\mu_0} \varepsilon_{0d} < 0$ (see inset in Figure 2a), and the graphene behaves like a thin metal plate capable of supporting the SPPs at such a wavelength. On the contrary, the same QD nearby the graphene with $\mu_c = 0.1$ eV does not lead to the excitation of the SPPs because $\varepsilon_{0d} > 0$ at $\lambda_{0d}$, and such graphene behaves like a dielectric. Note that the SPPs in a single graphene sheet are weak, and it is necessary to use a two graphene sheets waveguide arrangement\cite{55} to increase the power of surface waves. This requires additional tuning of the entire system.

Now we assume that the QDs are loaded into the center of the two graphene sheets plasmonic waveguide\cite{34} and used to pump the SPPs, as shown in Figure 1. Taking into account the influence of the rate of nonradiative decay on a waveguide system is of fundamental importance when choosing its parameters.\cite{45} Therefore, we optimize the system parameters in order to reduce the contribution of radiation and phonon losses and to obtain the maximum possible rate of SPP generation $\Gamma_{\text{SPP}}$ in two stages. At the first stage, using simple analytical calculations,\cite{29} we select a suitable combination of QD radius and its distance to a single graphene sheet. At the second stage, we place the QD inside the waveguide at an analytically determined distance from

![Figure 2.](Image)

Figure 2. a) Real (solid curves) and imaginary (dashed curves) parts of the total conductivity $\sigma = \sigma^R + i\sigma^I$ electric conductivity of graphene normalized to $\sigma_0$ versus free-space wavelength for chemical potential $\mu_1 = 0.1$ eV (red curves), $\mu_2 = 0.3$ eV (blue curves); the inset: real (solid curves) and imaginary (dashed curves) parts of graphene permittivity $\varepsilon_g$ versus free-space wavelength for chemical potential $\mu_1 = 0.1$ eV (red curves), $\mu_2 = 0.3$ eV (blue curves). b) Dimensional dependence for the wavelength of the interband transition of Ag$_2$Se QDs with effective masses of the electron $m_c = 0.32m_0$ and the hole $m_h = 0.54m_0$, and $\varepsilon_d = 11$ and $E_t = 0.07$ eV.
both sheets, and using numerical simulation, we adjust the system parameters in such a way that the brightness of SPPs generated in the system to be maximum. More accurate calculation of radiative and nonradiative linewidths of excitons in hybrid systems requires the use of successive derivation based on quantum mechanical perturbation theory. At the same time, we consider the QDs as small defects that slightly change the kinetics of the propagating SPPs. Therefore, the dispersion equation for the SPP propagating in such a QD-loaded two graphene sheets waveguide can be considered as the dispersion equation for two graphene sheets waveguide without QDs written in the form

\[ -k_h (\pm e^{-k_h d} - 1) = 2ik_0 \varepsilon_s \varepsilon_0 / \sigma \]  

where \( k_h = \sqrt{\beta^2 - k_d^2} \), \( \beta \) is the propagation constant of the SPP, \( d \) is the distance between the sheets, \( k_0 = \frac{2\pi}{\lambda} \) is the wave vector of the incident electromagnetic field at wavelength \( \lambda \) in a vacuum, and \( \varepsilon_d = 1.619 \) is the permittivity of the SiO\(_2\) at \( \lambda_0 = 5.864 \) nm as a dielectric material surrounding the waveguide. Note that decreasing distance \( D \) between QDs leads to an increase in the near field proportional to \( D^{-3} \). In this case, DDl can dominate on SPP generation, and energy transfer in such a waveguide with densely placed QDs occurs between QDs in the chain by means of DDl, and Equation (5) is not applicable. The study of such a regime requires the consistent consideration of the role of DDl between QDs placed inside the waveguide in the condition of development of plasmonic-assistant effects, including nonlinear effects.

Two dispersion branches for the two graphene sheets SPPs corresponding to the QD resonance wavelength \( \lambda_0 = 5.864 \) nm are presented in Figure 3a. Here, the red (blue) curve corresponds to the symmetric \( \beta_s \) (antisymmetric \( \beta_a \) ) mode, but we use only the symmetric mode \( \beta_s \) since it concentrates as much energy as possible into the space between the sheets of the plasmonic waveguide. We choose \( d = 14 \) nm for the strong coupling regime of the SPP in graphene. This regime satisfies the condition \( d < \xi \) because, in our case, \( \xi = \text{Re}(\frac{1}{\omega_0 e_k}) = 23.71 \) nm. The quantity of \( \xi \) is exactly the effective mode width of SPPs in graphene or plasmonic thickness of graphene. The condition \( d < \xi \) corresponds to the strong interplay of individual SPPs, and the wave vectors of the collective SPPs could be very different from SPPs propagating along a single graphene sheet. In this case, most of energy is carried in the dielectric between sheets for symmetric mode, which corresponds to SPP mode with small losses. The wavelength of the SPPs generated in a graphene waveguide is \( \lambda_{SPP} = \frac{2\pi}{\sqrt{\varepsilon_s \varepsilon_0}} = 58 \) nm and the propagation length is \( L_{SPP} = \frac{\lambda_{SPP}}{4 \text{Im}(\varepsilon_d)} = 250 \) nm, where \( n_{sp} = \frac{\mu_s}{\mu_m} = 101 \) is the effective refractive index of the SPP. These values are in good agreement with the electromagnetic simulation results based on the finite difference time domain (FDTD) method, which we have realized by ourselves. At the same time, the chosen distance between graphene sheets \( d = 14 \) nm corresponds to almost minimum of \( \text{Im}(\varepsilon_d) \) and, consequently, to the maximum of propagation length \( L_{SPP} \) for symmetric SPP mode at a given wavelength \( \lambda_0 = 5.864 \) nm (see inset in Figure 3a).

We performed numerical simulation for SPP propagation in the presence and in the absence of 5.794 nm \( \text{As}_2\text{Se}_3 \) QDs in the graphene-gold waveguide, when the QDs work as passive elements, that is, they are not pumped by an external optical field and are located only in the field of propagating SPPs. The SPP wavelength is almost the same for both models. Therefore, we use \( \lambda_{SPP} \) obtained from Equation (5) for determining the distance between QDs in order to tune the system to the desired type of interference. Additionally, we carried out the numerical simulation in the absence of hBN layers. In this case, the amplitude of the electric field distribution changes, but the SPP wavelength remains almost the same; therefore, we do not take into account the hBN layers in Equation (5).

To control the kinetics of the SPPs generated in a plasmonic waveguide loaded with QDs, it is sufficient to change the electron density of the states either on one or both sheets. This can be done by applying the voltage independently to each graphene sheet (first capacitor plate) to change their chemical potential. In particular, the value of the chemical potential of graphene is determined by surface carrier density in graphene and significantly increases following the increase in the surface carrier density in the region of the gold stripe (second capacitor plate) located. At the same time, a set of tasks has to be solved for this...
implementation. In particular, if we use graphene plates on a substrate rather than single flakes, then the electron density distribution will initially be quite unstable and inhomogeneous. A good solution is to use hBN as a buffer layer that significantly increases the homogeneity of the electron density in graphene (see Figure 1). In addition, high values of the field strength of the dielectric breakdown of the material make it possible to up the control voltage and vary the graphene chemical potential in a broader range.\[35\]

For simulation, we use the parallel-plate capacitor model, where the graphene carrier density \( n \) is given as follows:\[12,13\]

\[
n_{c} = \frac{\varepsilon_{SiO_2} \varepsilon_{0} U}{\varepsilon_{st} c} \tag{6}
\]

where \( U \) is the applied voltage, \( \varepsilon_{SiO_2} = 3.9 \) is the static dielectric constant of SiO\(_2\)\[99\] and \( h \) is the thickness of gate dielectric (SiO\(_2\)). For the undoped (ungated) graphene, the chemical potential \( \mu = 0 \) eV, but we consider the conventional commercial graphene with the initial chemical potential \( \mu_{0} = 0.1 \) eV corresponding to initial graphene carrier density \( n_{0} \) given by\[12,13\]

\[
n_{c} = \frac{2}{\pi \hbar^{2} u_{F}^{2}} \int_{0}^{\infty} d\varepsilon \left( f_{d}(\varepsilon) - f_{d}(\varepsilon + 2\mu_{0}) \right) \tag{7}
\]

where \( f_{d}(\varepsilon) \) is the Fermi-Dirac function with chemical potential \( \mu_{0} \) and \( u_{F} = 10^{6} \) m s\(^{-1}\) is the Fermi velocity. In this case, the total graphene carrier density is determined by induced \( n_{s} \) and initial \( n_{0} \) values and is written in the form\[12,13,60\]

\[
n_{c} + n_{0} = \frac{2}{\pi \hbar^{2} u_{F}^{2}} \int_{0}^{\pi} d\varepsilon \left( f_{d}(\varepsilon) - f_{d}(\varepsilon + 2\mu_{c}) \right) \tag{8}
\]

In order to satisfy the condition \( \hbar \omega < 2\mu \), under the chosen wavelength of the irradiation wave \( \lambda_{spp} = 5.864 \) \( \mu m \), the chemical potential of graphene should be increased. Therefore, we apply the negative electric potentials to the graphene sheets for increasing the surface carrier (electron) density of graphene according to Equation (8). Considering the 50 nm thickness of the SiO\(_2\) layer between hBN and Au, the voltage 13.7 V is sufficient to increase the chemical potential of graphene from initial 0.1 up to 0.3 eV (see Figure 3b). The main point is that, under the chosen conditions, a two parallel graphene sheets plasmonic waveguide does not support the SPP modes if no external voltage is applied. In contrast, the SPPs are formed in accordance with Equation (5) with an applied voltage of 13.7 V corresponding to the graphene chemical potential of 0.3 eV. Then, when the circuit in Figure 1 is excited by a normally incident planar wave at a wavelength of 4.5 \( \mu m \),\[41\] the SPPs will be generated only in the area under the gold stripes with the applied voltage.

It should be noted that the field strength of dielectric breakdown for thin SiO\(_2\) film significantly increases upon decreasing the thickness from bulk to nanometer scale. For example, for the 30 nm thickness of SiO\(_2\) film, the dielectric strength is about 0.85 V nm\(^{-1}\).\[62\] In our case, the used potential difference of 13.7 V and 50 nm thickness of SiO\(_2\) lead to the electric field strength 0.274 V nm\(^{-1}\) and, according to estimates, the dielectric breakdown does not occur between gold contact and graphene.

3. Results: Voltage Control of Collective Near-Field Effects in Plasmonic Gold/Graphene Waveguides Loaded with Ag\(_2\)Se Quantum Dots

The amplification and concentration of the near-field energy localized in a plasmonic waveguide can be realized by using an array of QDs and the synchronization of their responses. Such synchronization is achieved by varying the QD array period in the waveguide and tuning the voltage applied to graphene. First, we select the period \( P \) of the QD array so that it is a multiple of the wavelength of the generated SPP, that is, \( P = n\lambda_{spp} \), \( n = 1, 2, 3, \ldots \).

Here, we use the home-made implementation of the FDTD method verified by comparing simulation results with commercial software and other authors.\[35\] In our model, the grid step \( h = 2 \) nm which is greater than the real thickness of graphene 3.3 nm. Therefore, we choose \( \Delta = 2 \) nm and use the effective dielectric permittivity (1). The optical properties of the resulting model material fully correspond to the real graphene sheet.\[35\] In this work, we consider hBN as a few-layer dielectric with a thickness of \( \Delta_{hBN} = 2 \) nm that equals to grid step. We take into account the dependence of the permittivity on its thickness\[60\] and used \( \varepsilon_{hBN} = 3.6 \) for simulation. In addition, we simulate QDs inside a graphene waveguide as the electric dipoles excited by an external CW pump and oriented along the z-axis. Figure 4a shows the regime corresponding to the first order constructive interference for the SPP with \( \lambda_{spp} = 58 \) nm in the plasmonic waveguide in accordance with Equation (5). Here, the external voltage \( U = 13.7 \) V is applied to each graphene sheet to achieve the chemical potential value \( \mu_{c} = 0.3 \) eV. In this case, the strong collective response of the QDs creates a powerful SPP mode, which is localized in the space between the graphene sheets. Switching off the voltage on both sheets in Figure 4b returns the chemical potential of graphene to the value \( \mu_{c} = 0.1 \) eV, which results in a sharp decrease in the near-field intensity inside the waveguide due to the violation of the SPP generation conditions and the constructive interference for the QD array. The deposition of the metal stripes on the silica substrate in the required places allows routing of the SPPs generated by the excited QDs. At the same time, the other QDs located inside the plasmonic waveguide and outside the metal stripes are also excited by an external wave, but their energy is dissipated without the SPP generation since here \( \hbar \omega > 2\mu \). From a technical perspective, the random distribution of the QDs in a waveguide is simpler to implement, more robust, and amenable to practical applications. However, the generated SPPs in such a waveguide with an applied voltage of 13.7 V behave unstably, making them difficult to use for near-field concentration and routing (see Figure 4c).

We choose such topology in Figure 4d that the QDs can be used as sources of the SPPs generated in the space between the graphene sheets and the control gold stripes. In the latter case, the SPP wavelength in the gold stripes waveguide is 3300 nm, which was obtained from the direct numerical simulation (see Figure 4d). This wavelength corresponds to the SPP-SPP modulation, which should be attributed to the interaction and the near-field energy repumping between the graphene-localized SPPs and the gold-localized SPPs. Note that in Figure 4a, the chosen cell length \( P = 290 \) nm with periodic boundary conditions is significantly smaller than SPP wavelength in an external
Figure 4. Summarized electric field distributions (arbitrary unit) for a fragment of an infinite waveguide loaded with 5.794 nm Ag$_2$Se QDs and the distance between the graphene sheets 14 nm for a) the first-order constructive interference for SPPs via an applied voltage $U_1 = U_2 = 13.7$ V ($\mu_c = 0.3$ eV for both sheets), b) the near-field pattern for the no-voltage case ($\mu_c = 0.1$ eV for both sheets), and c) the near-field pattern for random QDs distribution and $U_1 = U_2 = 13.7$ V. d) The SPP-SPP modulation in the finite plasmonic gold/graphene waveguide with the first-order constructive interference for the graphene SPPs ($U_1 = U_2 = 13.7$ V). The thin magenta lines and the yellow bands depict the hBN layers and the gold stripes, respectively. The black lines correspond to graphene; the solid white lines depict the circle shape of the QDs. All plots are calculated for $\lambda_0 = 5.864$ μm.

gold waveguide; therefore, they cannot be observed. At the same time, the reason for SPP-SPP modulation in Figure 4d is the interference in the external gold waveguide that leads to non-homogeneous redistribution of QDs energy and amplification of graphene SPPs in the regions of interference maximums of the gold waveguide. At the same time, we do not consider the change in the electron density on the live gold contacts, but this correction will be negligible. As a result, the internal graphene waveguide acts as an efficient near-field pumping for the external gold waveguide. Note that the injection of defects by removing one or several QDs from the circuit makes it possible to change the field distribution to the required localization in the waveguide. This effect can be used to pump nanostructures,[67] particularly the array of nanoantennas integrated or connected to a plasmonic waveguide. Additional control of the external voltage allows switching on/off and changing the emission regimes of an individual nanoantenna and varying the radiation pattern of all arrays, in general.

4. Conclusion

In this paper, we considered the graphene-based waveguide model loaded with the QDs whose electromagnetic properties are controlled by applying an external voltage. We optimized the parameters of two parallel graphene sheets and QDs to realize the controllable excitation of SPPs in the graphene waveguide. It was shown that as the control parameter of the system can be adopted, the magnitude of the applied voltages modifies the graphene chemical potential and leads to a change in the regime of the SPPs excitation. The controllable SPP excitation results in a high concentration of the near-field energy and its routing along the local paths determined by the spatial configuration of the applied external voltage.

In general, the presented system of the graphene waveguide loaded with QDs and the voltage control can be used to design ultra-compact optical devices for transport of the near-field energy, its concentration, and pumping of light-emitting nanostructures.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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