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Original Paper

# Non-equilibrium polaritonics - non-linear effects and optical switching

*Regine Frank**

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In this article a microscopic electronic non-equilibrium effect, highly nonlinear polaritonics, is proposed to mediate an ultrafast all-optical switching. The electronic band structure within gold (Au) nano grains shall be modified by external laser light, namely the Franz-Keldysh effect, and the modified electronic density of states within the Au grains are coupled to a single mode photonic waveguide. Using this microscopic polaritonic coupling without ever including any macroscopic influences due to the geometric arrangement a strong transmission reduction originating from the established quantum interference is derived. The lifetime of the coupled states is heavily dependent on the Fano resonance type binding and the amplitude of the applied electric field. Besides the Fano signatures the microscopic coupling photon-electron-photon leads to a gaped electronic density of states within the Au nano-grains.

## 1 Introduction

Plasmonics and polaritonics [1] may be the most promising candidates in the race of novel ultrafast technologies which have the potential to reach the application border [2–4]. Meta-materials or plasmonic systems [5] are on the edge to be engineered for ultrafast electronic switches [7–12], and ultrashort laser science opens the door to their exploration [13–15]. However discussing picosecond, femto- or attosecond time scales the framework of equilibrium physics reaches it's limits. When one speaks about ultrafast non-linear processes in commercially fabricated metallic or organic structures, impurities naturally play a key role for the efficiency and the proper operation of such devices. They may either disturb the process or may play the key role of access to new technologies. Another fascinating track of physics in the context of ultrafast switches are beyond doubt quantum-optical functional elements [16]. Yet the combination of both, highly non-linear non-equilibrium physics and quantum optics is an ansatz which has not been felt out in a broad range up to now. Solid-state-based elements, in that context, provide a number of advantages such as scalability, tunable light-matter interactions and comparably easy handling. Besides its immense technological importance, the theoretical description of externally driven quantum systems is a challenge itself, and vividly discussed [17–19]. While the basic underlying equilibrium physics for a system with discrete levels coupled to a continuum of states is well established [20–24], the profound description of light-matter interaction far away from thermodynamical equilibrium is an active and fascinating area [25] of research.

A very simple model to explore non-equilibrium effects is chosen here in form of a Fröhlich Hamiltonian which couples classically strong laser radiation to metal electrons. The modified density of states than interacts with the waveguide photons by means of a Fano resonance. That coupling is considered to be weak and therefore can be determined by second order perturbation theory. The model simply focuses on these very basic procedures and does not at all claim to be complete, especially geometric finite size effects for high field intensities are neglected by choosing spherical gold grains. Additionally possible interactions between the grains by scattered light is not considered here either. The pulse duration in what follows is chosen such that scattering of electrons within the metal can be neglected as well.

## 2 Franz-Keldysh effect and fano resonance

In this article the electronic properties of gold (Au) nano-grains exposed to an external field are investigated and

* Corresponding author E-mail: regine.frank@kit.edu
Institut für Theoretische Festkörperphysik, Karlsruher Institut für Technologie (KIT), Wolfgang - Gaede - Strasse 1, 76131 Karlsruhe, Germany

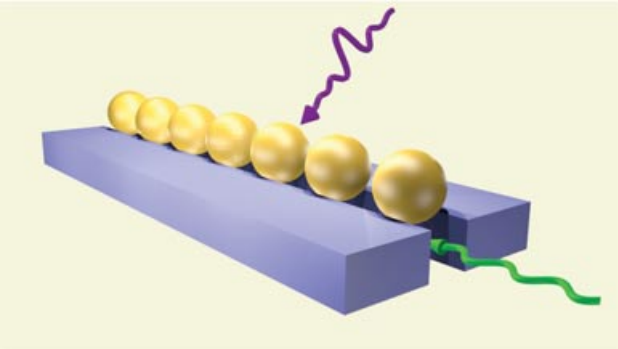

**Figure 1** (online color at: www.ann-phys.org) Sketched geometry. Gold nanograins in contact with a hollow core SOI waveguide. Waveguide photons (green) interact with electrons in the metal nano-grains (Au) forming a coupled light-matter state, a polariton. This is controlled by an external laser (pink), altering the transmission through the waveguide (green).

they are coupled to a single mode photonic silicon-on-insulator hollow core waveguide (SOI). In this non-equilibrium system, the external time-periodic field generates photo-induced electronic side-bands which can be attributed to the Franz - Keldysh effect, the AC analogon to the well known Wannier-Stark effect. Intraband transitions occurring in every metal within the conduction band feature a more or less small absorbtion rate, whereas the governing processes are the interband transitions. In Au a significantly different behavior has been found, which has been attributed to the electronic specific structure of closed packed Au, namely to the high polarizability of the $5d^{10}$ cores. The collective resonance exhibits a large red shift to approximately 2.4 eV which leads to the fact that the corresponding intensity is governed by the interband processes but its existence results from the occurrence of intraband transitions which can be recognized as step like structures in the spectrum. These transitions, which result from a non-Fermi alike distribution of states, have been observed by Whetten et al. [26], for Au nano-spheres of diameters below 30 nm. Their occurrence has been interpreted as the border from bulk like characteristics to the quantum regime of nano particles. The transitions within this single plasmon band provide the basis for the switching effect. It is shown that the bandstructure of the coupled system of Au nano-grains and SOI is strongly modified by intense external laser radiation (Fig. 4), which can be tested experimentally e.g. by two photon photoemission (2PPE). Frequency and amplitude of the external field can be separately used to modulate the position in energy of the Floquet sidebands and, therefore sensitively control the generation of a Fano-resonance with the photonic SOI mode. The calculated lifetimes of the coupled states prove the extremely fast switching.

## 3 Fröhlich Hamiltonian and Floquet-Keldysh method

As theoretical setup the Fröhlich Hamiltonian [27, 28] for fermion-boson interaction is chosen which is solved by applying the Keldysh formalism with respect to the non-equilibrium character of the considered processes on the femto-second time scale. The full

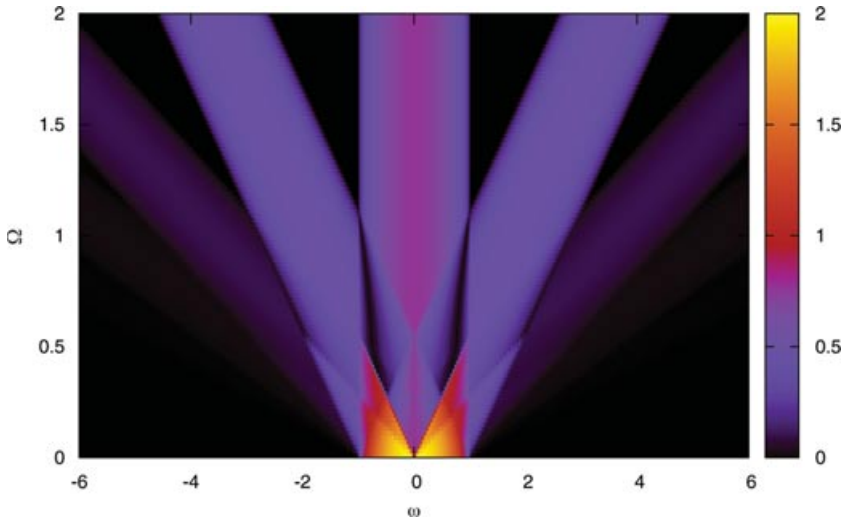


**Figure 2** (online color at: www.ann-phys.org) The imaginary part of the local Green's function, the local density of states (LDOS) Eq. (7), is depicted as a function of quasiparticle energy, and frequency respectively $\omega$ and external laser frequency $\Omega_L$ at zero temperature for external field amplitude $A_0/t = 4.0\,\mathrm{eV}$. The original semicircular DOS evolves photonic side-bands as the laser frequency increases. Sidebands of first and second order can be identified for this specific value of field amplitude.

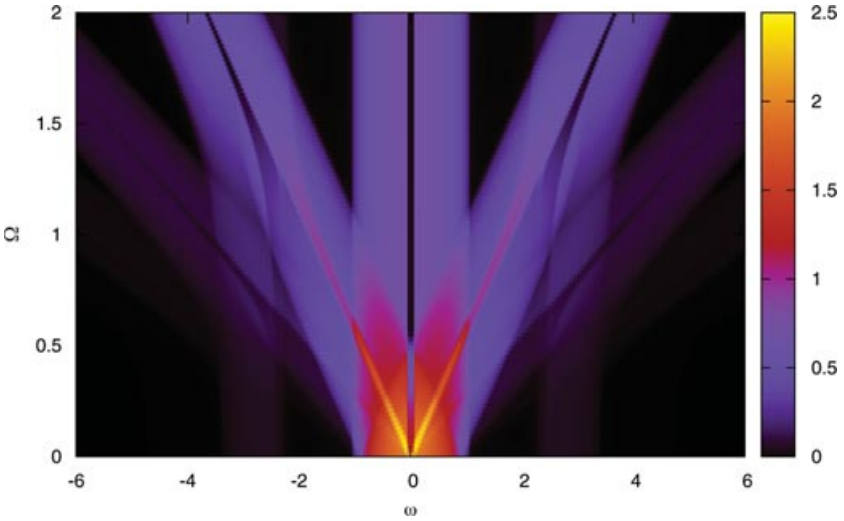


**Figure 3** (online color at: www.ann-phys.org) Depicted is the imaginary part of the full Green's function, including all interactions as a function of frequency $\omega$ and external frequency $\Omega_L$ at zero temperature. The external amplitude is chosen to be $A_0/t = 4.0$ (see text). The electronic Floquet-Keldysh (Fig. 2) bandstructure is modified by the coupling to the single mode waveguide operated at $\hbar\omega_0 = 2.34\,\mathrm{eV}$. The coupling is established by an electron-mediated Fano resonance. This Fano resonance results in an avoided crossing of bands at $\hbar\omega = 2.34\,\mathrm{eV}$ and $\hbar\Omega_L = 1.17\,\mathrm{eV}$. Spectral weight from the Fermi edge position in equilibrium is obviously shifted to the center of the Floquet sidebands by that coupling of gold and waveguide which results in the development of a gap in the center of the original band at $\omega = 0.0$. For all $\Omega$ the development of high (low) energy tails can be observed, which leads to the enhancement of excited bands due to the Fano resonance.

Hamiltonian reads

$$H = \sum_{k,\sigma} \epsilon_k c^\dagger_{k,\sigma} c_{k,\sigma} + \hbar\omega_o a^\dagger a + g \sum_{k,\sigma} c^\dagger_{k,\sigma} c_{k,\sigma} (a^\dagger + a) \qquad (1)$$
$$- t \sum_{\langle ij\rangle,\sigma} c^\dagger_{i,\sigma} c_{j,\sigma} + i\vec{d}\cdot\vec{E}_0 \cos(\Omega_L \tau)$$
$$\times \sum_{<ij>} \left( c^\dagger_{i,\sigma} c_{j,\sigma} - c^\dagger_{j,\sigma} c_{i,\sigma} \right).$$

The ingredients can be named as the electronic on-site term $\sum_{k,\sigma} \epsilon_k c^\dagger_{k,\sigma} c_{k,\sigma}$, the single waveguide mode $\hbar\omega_o a^\dagger a$, the perturbative coupling of electrons to waveguide photons (the polariton) $g \sum_{k,\sigma} c^\dagger_{k,\sigma} c_{k,\sigma} (a^\dagger + a)$, the nearest neighbor hopping of electrons in the lattice $-t \sum_{\langle ij\rangle,\sigma} c^\dagger_{i,\sigma} c_{j,\sigma}$, the classical coupling of the external electrical field amplitude to the dipole moment of metal electrons and the resulting contribution to the hopping (plasmon) $i\vec{d}\cdot\vec{E}_0 \cos(\Omega_L\tau) \sum_{<ij>} \left( c^\dagger_{i,\sigma} c_{j,\sigma} - c^\dagger_{j,\sigma} c_{i,\sigma} \right)$.

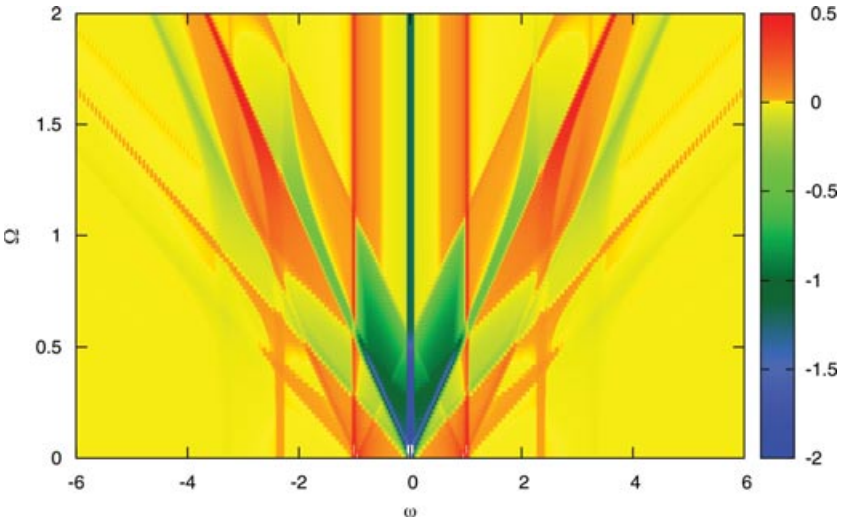


**Figure 4** (online color at: www.ann-phys.org) Laser induced change of the electronic density of states $\delta G(\omega, \Omega_L)$, Eq. (8). The photonic waveguide mode $\hbar\omega_0 = 2.34\,\mathrm{eV}$, the coupling between waveguide photons and electrons is $g/t = 0.3$ ($\sim 30\%$ of the coupling $A_0$), the temperature $T_0 = 0$ and the amplitude $A_0/t = 4.0$ (see text). $\delta G$ displays a Fano resonance around quasiparticle frequencies $\omega = \omega_0$, i.e. as soon as the external laser field redistributes the electronic spectral weight such, that the waveguide mode finds electrons with about the same energy to efficiently interact with.

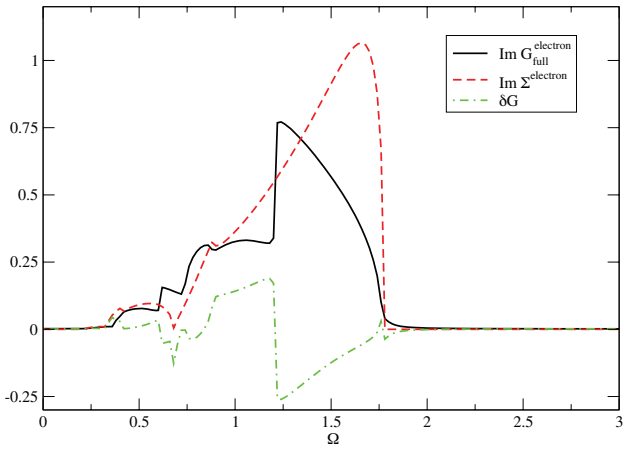


**Figure 5** (online color at: www.ann-phys.org) The imaginary part of the retarded component of the full electronic Green's function $\Im G$ is shown in combination with the imaginary part of the retarded component of the electronic selfenergy $\Im\Sigma$ and the imaginary part of the difference Green's function $\delta G$ as defined in the text, for the electronic energy of $\hbar\omega = 2.34$ eV and for a range of external pump laser frequencies $\Omega_L$. At a about $\hbar\Omega_L = 1.2$ eV the sharp dip in $\delta G$ indicates the maximum modulation in the transmittance of the waveguide mode due to the strong coupling to the nanograins. That point of switching corresponds t a maximum change of spectral weight in the electronic density of states $\Im G$. The inverse lifetime $\Im\Sigma$ is found to be finite valued and the corresponding lifetime of the states equals $t = 5.908 \cdot 10^{-15}\ s$. The element can be operated having very short dead times.

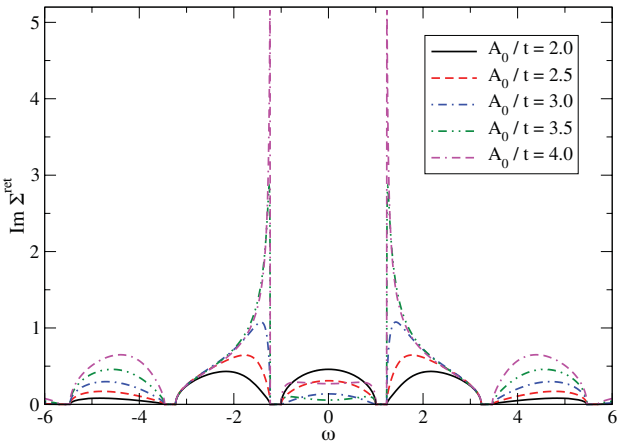


**Figure 6** (online color at: www.ann-phys.org) The imaginary part of the retarded component of the electronic selfenergy $\Im\Sigma$ is shown for the external field amplitudes $A_o$ assuming 2.0, 2.5, 3.0, 3.5 and 4.0. $\Im\Sigma$ is proportional to the inverse lifetime of the electronic excitations. The development of the inverse lifetime at external field frequency $\hbar\Omega_L = 1.24$ eV corresponding to the switching parameters in the text is displayed. It can be found that the inverse lifetime for increasing external field amplitude drastically increases. The liftime therefor decays fast (see text). The change of the lifetime of states in experiments indicates non-equilibrium behavior.

This article is organized as follows, considered is (i) the waveguide in contact with nano-grains, (ii) the nano-grain in the external field and finally (iii) the non-equilibrium solution of the complete system in terms of electronic Keldysh - Green's function and waveguide transmission are discussed. The overall switching is measured as the difference between density of electronic states of the totally unaffected system compared to the setup including all effects due to the external laser light and as a consequence the coupling to the waveguide mode.

As starting point it is chosen a single electron band with nearest-neighbor hopping, characterized by the hopping amplitude $t$, with the dispersion for a cubic lattice for the ion cores $\epsilon_k = 2t\sum_i \cos(k_i a)$, $a$ is the lattice constant and $k_i$ are the components of the wave-vector. A SOI waveguide supporting a single mode $\hbar\omega_0 = 2.34$ eV. The waveguide itself is coated and not exposed to the external laser field is assumed, therefore just metal electrons may interact with the external field and the waveguide is not affected directly. The electrons couple with strength $g$ weakly to waveguide photons with frequency $\omega_0$. A possible setup is depicted in Fig. 1. The Hamiltonian without the external laser field reads,

$$H = \sum_{k,\sigma} \epsilon_k c^\dagger_{k,\sigma} c_{k,\sigma} + \hbar\omega_o a^\dagger a + g\sum_{k,\sigma} c^\dagger_{k,\sigma} c_{k,\sigma}(a^\dagger + a). \qquad (2)$$

The spatial extension of the Au nano-grains is assumed to be smaller than 30 nm, and consequentially small compared to the wavelength of the photonic mode inside the waveguide. Therefore, the momentum of the photons is much smaller than the electron's momentum and it can be set $q_{\text{photon}} \simeq 0$ whenever one considers the electronic subsystem. Thus, $a^\dagger$ ($a$) does not carry an index in the Hamiltonian. In Eq. (2), $\epsilon_k$ is the electronic band energy, $c^\dagger_{k,\sigma}$ ($c_{k,\sigma}$) creates (annihilates) an electron with momentum $k$ and spin $\sigma$. $\hbar\omega_0 a^\dagger a$ is the photon energy eigen-state, where $a^\dagger$ ($a$) creates (annihilates) a photon inside the waveguide with energy $\hbar\omega_0$. The last (coupling) term on the r.h.s. is the standard coupling term between the electronic and the photonic subspaces [29]. Due to the weak interaction of waveguide photons and electrons inside the nano-grains this interaction is treated perturbatively. In second order a self-energy contribution is obtained from Eq. (2). The coupling of the electronic system with a continuous energy spectrum to the photons with a discrete one leads to a so-called Fano resonance [20]. This is observed in the electronic density

of states (see Fig. 3). Here is shown the electron's spectral function for various frequencies of the waveguide mode for coupling strength $(g/t)^2 = 0.09$ at zero temperature $T_0$ for a Lorentzian spectral width $w = 0.005$ of the waveguide mode (measured in units of the hopping $t$) at half filling, yielding a suppression of the spectral function around the Fermi-level (half width $w$) where electrons are transferred to the high (low) energy tails of the spectral function. Besides the Floquet sidebands the these band structures can be identified between $\omega = \pm 2.34$ and $\omega = \sim \pm 3.7$ for all $\Omega_L$. Their band edges can be even better identified to be at $\omega = 2.34$ within the laser induced change of the electronic density (see Fig. 4). It is noted, that if the energy of the waveguide mode $\hbar\omega_0$ is distinctly different from the energy $\hbar\omega$ of the band-electrons, the electronic density of states remains approximately unchanged.

Now the subsystem of a nano-grain exposed to a semiclassical electromagnetic laser field is discussed. This is described by the Hamiltonian (Lb = laser +band-electrons)

$$H_{Lb} = -t\sum_{\langle ij\rangle,\sigma} c^\dagger_{i,\sigma} c_{j,\sigma} + H_C(\tau) \tag{3}$$

where $\langle ij\rangle$ implies summation over nearest neighbores. $H_C(\tau)$ represents the coupling to the external, time-dependent laser field, described by the electric field $\vec{E} = \vec{E}_0 \cos(\Omega_L \tau)$, via the electronic dipole operator $\hat{d}(\vec{x})$ with strength $\vec{d}$. It is given by

$$H_C(\tau) = i\vec{d}\cdot\vec{E}_0 \cos(\Omega_L\tau) \sum_{<ij>} \left( c^\dagger_{i,\sigma} c_{j,\sigma} - c^\dagger_{j,\sigma} c_{i,\sigma} \right). \tag{4}$$

The Hamiltonian specifically describes the excitation of a plasmon-polariton, which correspond to spatially delocalized intraband electronic motion caused by an external electromagnetic wave. The accelerating energy is immediately transferred into the motion of electrons by means of single-band nearest neighbor hopping without interaction between the electrons. Due to the time dependence of the external field, Green's functions truly depend on two separate time arguments $\tau_1$ and $\tau_2$. Therefore, a double Fourier transform from time- to frequency space introducing relative and center-of-mass frequency is used [30]

$$\begin{aligned} G^{\alpha\beta}_{mn}(\omega) &= \int \mathrm{d}\tau_1^\alpha \int \mathrm{d}\tau_2^\beta \, e^{-i\Omega_L(m\tau_1^\alpha - n\tau_2^\beta)} e^{i\omega(\tau_1^\alpha - \tau_2^\beta)} G\left(\tau_1^\alpha, \tau_2^\beta\right) \\ &\equiv G^{\alpha\beta}(\omega - m\Omega_L, \omega - n\Omega_L), \end{aligned} \tag{5}$$

where $(m, n)$ label the Floquet modes [31] and $(\alpha, \beta)$ specify on which branch of the Keldysh contour $(\pm)$ the respective time argument resides. Floquet states are the fouriertransformed analog to Bloch states: The first ones result from a time-periodic potential whereas the latter are the result of a space-periodic potential and both induce a band-structure. The special case of non-interacting electrons allows an analytical solution for $G_{mn}(k, \omega)$ by solving the equation of motion. Including photo-induced hopping, the exact retarded Green's function for this sub-system has also been discussed in different context e.g. [19]

$$G^R_{mn}(k, \omega) = \sum_\rho \frac{J_{\rho-m}(A_0\tilde{\epsilon}_k)\, J_{\rho-n}(A_0\tilde{\epsilon}_k)}{\omega - \rho\Omega_L - \epsilon_k + i0^+} \tag{6}$$

where $\tilde{\epsilon}_k$ represents the dispersion relation induced by the external field Eq. (4) and is different from $\epsilon$ Eq. (2). The $J_n$ are the cylindrical Bessel functions of integer order, $A_0 = \vec{d}\cdot\vec{E}_0$ and $\Omega_L$ is the laser frequency. The Bessel function indicate the highly non-linear characteristics of the switching effect under investigation. The physical Green's function is given according to

$$G^R_{\mathrm{Lb}}(k, \omega) = \sum_{m,n} G^R_{mn}(k, \omega). \tag{7}$$

A numerical evaluation of Eq. (7) in Fig. 2 is presented, where Im $G^R_{\mathrm{Lb}}(k, \omega)$, is displayed as a function of quasiparticle energy $\hbar\omega$ and external frequency $\Omega_L$ at zero temperature for $A_0/t = 4.0$. As a typical value for the hopping $t = 1$ eV is chosen. The waveguide is operated at the frequency $\hbar\omega_0 = 2.34$ eV which corresponds to a frequency doubled Nd-YAG laser ($\hbar\omega_0 = 1.17$ eV). The external laser shall be characterized by 10 fs pulses, and shall be $E_0 = 1.008 \times 10^{10}$ V/m in the surface region of the Au grains, including Mie type [32] field enhancement effects due to the small particle sizes [33–35]. For the nano-grains a damage threshold [36] of 0.5J/cm$^2$ and $|d| = 6.528 \times 10^{-29}$ Asm (with the lattice constant for Au $a_{Au} = 4.08 \times 10^{-10}$ m) is feasable, resulting [37] in $A_0 \equiv d \cdot E_0 = 4.0$ eV. Furthermore a waveguide with length 10 μm with a density of 50% nanograins is assumed. The original semicircular density of states develops photonic side-bands, the bandstructure, as the external laser frequency $\Omega_L$ increases. Due to the point-inversion symmetry of the underlying lattice, the first side-band represents here the two-photon processes. The less pronounced second side-band, therefore, represents four-photon processes. Their occupation is described by the non-equilibrium distribution function as calculated from the Keldysh component of the Green's function.

In a last step, the relaxation processes due to the interaction between the band electrons and the waveguide as described by Eq. (2) are combined, with the impinging external laser as introduced in Eq. (3). The resulting Green's function consequentially describes the photonic waveguide with Au nano-grains that themselves are now exposed to the external laser radiation. In this non-equilibrium system the weak coupling between the electrons and the waveguide photons is treated by second order perturbation theory and the interaction between the electrons and external laser in terms of the Floquet theory, as has been shown above.

Since the focus lies on possible switching effects, the initial situation is chosen such that the photonic mode, $\hbar\omega_0 = 2.34\,\mathrm{eV}$, is far off the electronic bandedge. Electrons arrive band energies ranging from $-1 \leq \hbar\omega/t \leq +1$. A Fano resonance is only observable in the presence of external radiation of appropriate frequency, i.e. only if the induced side-bands meet the energy of the waveguide mode. This resonance will also affect the transmission properties in the waveguide, since now waveguide photons can be absorbed in the formation of a mixed state of light and matter with the laser-induced charge excitations in the Au nano-grains. Thus a waveguide polariton is created yielding to a significant reduction of the waveguide's transmission. In Fig. 4, the laser induced change of the density of states $\delta G$ as a function of quasiparticle energy $\hbar\omega$ and external laser frequency $\Omega_L$ is displayed. The quantity $\delta G$ defined according to

$$\delta G = [\mathrm{Im}\, G(\omega, \Omega_L) - \mathrm{Im}\, G_{\mathrm{Lb}}(\omega, \Omega_L)] - [\mathrm{Im}\, G_{\mathrm{wb}}(\omega) - \mathrm{Im}\, G_{\mathrm{b}}(\omega)] \quad (8)$$

measures the effect of the impinging laser field on the electronic density of states, and vanishes as the external laser and the coupling to the waveguide is turned off. In Eq. (8), $G$ represents the Green's function including all processes, $G_{\mathrm{Lb}}$ the interaction between the laser field and the band electrons as given in Eq. (7), $G_{\mathrm{wb}}$ describes the waveguide in presence of the band electrons and is solution to Eq. (2), and finally $G_{\mathrm{b}}$ is the Green's function of just the non-interacting band electrons. In Fig. 3 the laser induced electronic density of states coupled to the waveguide $G(\omega, \Omega_L)$ experiences a Fano resonance as soon as the external laser redistributes electronic spectral weight such, that the waveguide mode at $\hbar\omega_0 = 2.34\,\mathrm{eV}$ may efficiently be absorbed. This is derived when the first photonic side-band meets the energy of the photonic waveguide mode yielding a sign change in $\delta G$ at this energy; compare also to Fig. 2. Additionally, one finds in Fig. 3 at this particular point an avoided crossing of the bands. In Fig. 4, the laser induced change

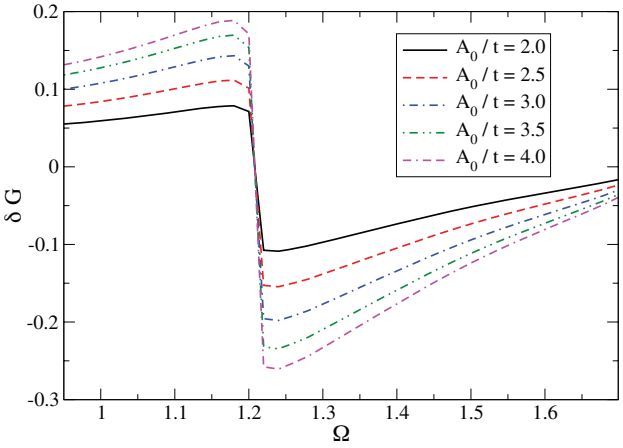


**Figure 7** (online color at: www.ann-phys.org) The relative switch of electronic density of states $\delta G$ is a measure for the dip in the transmission of waveguide photons and therefore the inverse polaritonic coupling between waveguide photons and electrons. The waveguide is of unit length $l = l_o$. The graph is displayed as a function of external laser frequency $\Omega_L$, for four different amplitudes of the external field. Parameters are given in the text.

of the electronic density of states $\delta G$ is shown at fixed quasiparticle energy $\hbar\omega = \hbar\omega_0$, where $\omega_0$ is the frequency of the photonic waveguide mode. Asymptotically, i.e., for large $\Omega_L$, $\delta G$ vanishes, as already indicated in Fig. 2, because in this limit there is no electronic spectral weight at the particular energy of the waveguide mode. In the opposite limit, $\Omega_L \to 0$, the influence of the laser field is non-zero, because here higher-order laser induced side-bands exist, yielding spectral weight at the resonance position already for smaller laser frequencies. That result can also be concluded from the second-order side-band in Fig. 3.

In a waveguide of length $l$, the ratio between the initial and the transmitted intensity is given by $T \sim \exp(-\alpha\, l/\, l_o)$. Here $\alpha/\, l_o$, is the absorption coefficient divided by the unit length $l_o$, where $\alpha$ includes an average over one period of the external periodic driving field with frequency $\Omega_L$. It can be recognized that $\omega\delta G$ can be understood as the leading contribution to the relative absorption coefficient as discussed in detail in Ref. [42]. In Fig. 8 is shown the relative transmission of photons $T/\, T_0$ within the waveguide of unit length $l = l_o$ as a function of the external laser frequency $\Omega_L$. Depending on the frequency of the driving field, an intensity drop of up to 25% is observed (see Fig. 7). By increasing the length of the waveguide or the density of the grains this effect is enhanced. Therefore one can conclude, that by switching laser light of an appropriate frequency of about $\hbar\Omega_L/\, t \sim 1.35$, the transmitted photon intensity through

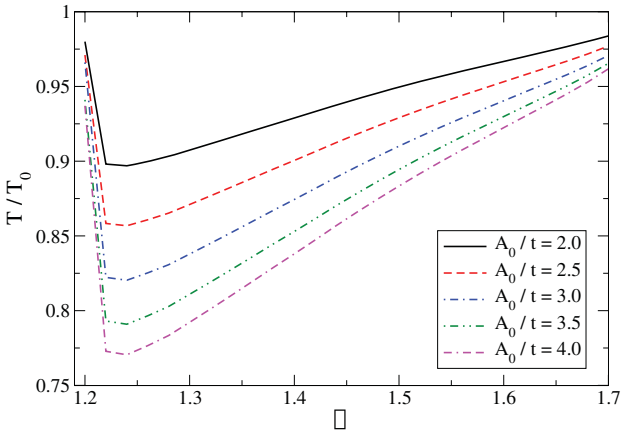


**Figure 8** (online color at: www.ann-phys.org) Relative photon transmission in a waveguide of unit length $l = l_o$ as a function of laser frequency $\Omega_L$, for four different amplitudes of the external field. Parameters are given in the text.

the waveguide can be significantly altered, and by varying the length of the waveguide the transmission inside the waveguide can in fact be turned on and off. The calculated lifetime (see Fig. 5) of the coupled state in the position of the Fano resonance for the presented parameters equals $t = 5.908 \cdot 10^{-15}\, s$. After that reaction time the switch should be in the initial state and ready for the next signal. In Fig. 6 the evolution of the corresponding lifetimes with increasing external laser amplitude is discussed. It is found, that the Floquet sidebands evolve with raising field amplitude and so does the calculated inverse lifetime. The inverse lifetime of coupled states with raising field amplitude is diminished. It can be clearly observed, that the minimum is shifting with increasing amplitude towards the position of the lower band edges for $\omega > 0$ and to the upper band edges for $\omega < 0$.

## 4 Conclusion

To conclude: In this article a quantum field theoretical model for a photonic waveguide in contact with gold nano-grains which themselves are exposed to external laser irradiation has been presented. The strong and coherent external laser is described in terms of the Floquet theory, assuming classical behavior of this oscillatory-in-time field, whereas the interaction with the waveguide mode reflects a quantum interference. The obtained results demonstrate the high potential of waveguide polaritons for all-optical switching. Both, frequency and amplitude of the external laser control transmission through the waveguide, and each of these features ensure ultrafast switching processes.

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**Key words.** Non-equilibrium, ultrafast effects, optical switching.

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