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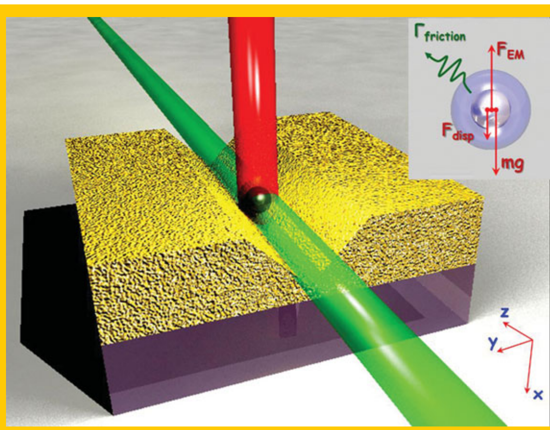
ORIGINAL PAPER

Abstract In order to achieve interaction between light beams, a mediating material object is required. Nonlinear materials are commonly used for this purpose. Here a new approach to control light with light, based on a nano-opto-mechanical system integrated in a plasmonic waveguide is proposed. Optomechanics of a free-floating resonant nanoparticle in a subwavelength plasmonic V-groove waveguide is studied. It is shown that nanoparticle auto-oscillations in the waveguide induced by a control light result in the periodic modulation of a transmitted plasmonic signal. The modulation depth of 10% per single nanoparticle of 25 nm diameter with the clock frequencies of tens of MHz and the record low energy-per-bit energies of 10^{-18} J is observed. The frequency of auto-oscillations depends on the intensity of the continuous control light. The efficient modulation and deep-subwavelength dimensions make this nano-optomechanical system of significant interest for opto-electronic and opto-fluidic technologies.



Nano-opto-mechanical effects in plasmonic waveguides

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1. Introduction

Generation of optical pulses generally relies on electronically-driven modulation of continuous light beams and laser resonators with mode-locking or Q-switching options [1]. All-optical approaches based on interacting light beams require mediating materials to induce nonlinear interaction and pulsed control light. The need to reduce control light intensities has led to extensive development of various nanostructures with enhanced nonlinearities [2]. Opto-mechanical effects in nanostructured environment may provide new, alternative opportunities to achieve efficient nanophotonic modulators without the need of nonlinear materials, integratable in a waveguide and opto-fluidic circuitry.

Opto-mechanics deals with both optical effects induced by mechanical motion and, other way around, mechanical effects induced by optical forces. For example, opto-mechanical interactions in optical cavities can be used as very sensitive, innovative measurements tools, e.g., for detection of gravitational waves [3]. On the other hand, the concept of optical forces has been employed in laser cooling (or radiation pressure cooling) [4], precise particles' sorting [5], artificial light crystals (optical lattices) [6], quantum computing [7], solar sails [8], studies of conformations events at molecular level [9], and many other areas. Optical control of nano- and microscale particles is paramount for development of next generation of lab-on a chip optofluidic [10] and sensing applications as well as for advanced nano-opto-mechanical (NOM) systems for photonics. Typical optical forces achievable with reasonable light intensities are in the range from nano- to pico- Newtons, which creates certain limitations on the size of the objects to be manipulated due to their size, weight and stochastic interactions with surroundings.

One of the promising and already tested approaches for the optical force enhancement relies on the increase of the field gradient with the help of the so-called plasmonic nanostructures. Noble metals with negative permittivity at optical and infra-red wavelengths (plasmonic metals) can support surface plasmon modes with deep subwavelength localisation of the electromagnetic energy, overcoming the conventional diffraction limit and creating strong field gradients. The concept of plasmonic tweezers has advantages

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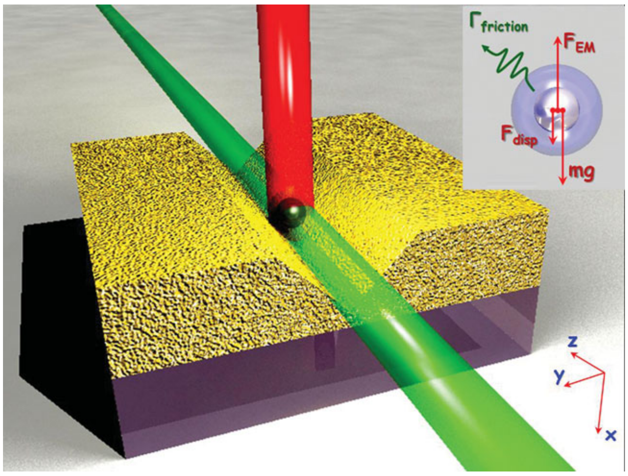

Figure 1 Schematics of NOM modulator: a nanoparticle in the V-grove waveguide is driven into oscillatory motion by control beam (red). The particle moves in and out of the fundamental mode of the waveguide (green) and modulates modal loss. Inset shows the forces acting on a nanoobject inside the V-groove.

by providing better spatial localization of objects and reduction of required illumination power due to the antenna effect of trapping structures [11].

Here, we have developed the concept of controllable nanoparticle motion in the electromagnetic field of a plasmonic waveguide, carefully maintaining the balance between optical and dispersion forces, enabled by the structured electromagnetic environment, to mediate light-light interaction without the need for optical nonlinearity. We have demonstrated the use of this effect for generation of waveguided pulse trains with clock frequencies determined by the intensity of the continuous control light.

2. The concept of nano-opto-mechanical light modulator

The concept of the proposed NOM modulator approach is depicted in Fig. 1. A nanoparticle is placed in the V-grove plasmonic waveguide, and its position is controlled by a control beam. The balance of forces keeps the particle levitating in the waveguide: while a control beam induced optical force tends to eject a nanoparticle from the bottom of the V-groove (proper design of surrounding photonic structure enables to focus the field below the particle and achieve counterintuitive pulling forces), the dispersion, friction, gravitational and optical force (pushing force in the upper part of the V-groove) keep it from moving out of the waveguide. In the presence of a control light, the particle oscillates in the waveguide, moving in and out the field of the plasmonic waveguided mode. This movement results in the increased or decreased losses of the mode, and, thus, the modulation of the waveguide transmission. The frequency of nanoparticle oscillations depends on the intensity of the control light which may be continuous (CW) or quasi-continuous. While many other realizations are possible, the use of plasmonic V-groove waveguide is potentially promising as it supports a subwavelength confinement and, at the same time, allows significant propagation distances [12] sufficient for device realizations [13].

3. Particle's motion in electromagnetic field in a waveguide

The Newton's equation of motion of the oscillating particle in the V-groove waveguide is given by

$$m\ddot{\mathbf{r}} = \mathbf{F}_{EM}(\mathbf{r}) + m\mathbf{g} + \mathbf{F}_{disp}(\mathbf{r}) + \Gamma_{friction}(\mathbf{r}) \cdot \dot{\mathbf{r}}, \quad (1)$$

where $\mathbf{r}$ is the particle's centre of mass coordinate, m is the particle's mass, $\mathbf{g}$ is the gravitational acceleration, $\mathbf{F}_{EM}(\mathbf{r})$ is the full electromagnetic force, $\mathbf{F}_{disp}(\mathbf{r})$ is the dispersion force (Van der Waals force) and $\Gamma_{friction}(\mathbf{r}) \cdot \dot{\mathbf{r}}$ is the friction force. The dispersion force is the manifestation of the virtual photons exchange between the particle and the rest of the environment resulting, generally, in the macroscopic attraction between neutral material bodies. This force can be estimated classically by summing up all induced dipole-dipole interactions at all frequencies [14] or quantum-mechanically using more advanced tools [15]. The main contributor to losses in the system in the absence of embedding media (a particle is considered in vacuum), will be the electromagnetic friction. This effect can be qualitatively explained by electrostatic image theory, the Ohm's and Joule-Lenz's laws. Dipole moment induced either by external illumination or, spontaneously, by vacuum fluctuations creates image charges. These charges move in the lossy metal, following the motion of the original source, if retardation is neglected. As the result of this, a part of the electromagnetic energy transfers into heat of the metal structure. Both dispersion forces and the spontaneous part of the electromagnetic friction are induced by vacuum fluctuations and independent of an external illumination. At the same time, the stimulated electromagnetic drag force is proportional to the illumination intensity. The stimulated force is predominant over spontaneous, if laser beam is of sufficient intensity [14]. Nevertheless, even being small, all dispersion and gravitational forces have been included in the considered model.

4. Optical forces acting on a nanoparticle in a waveguide

The most general approach to estimate electromagnetic forces acting on a nanoparticle is to employ the Maxwell's stress tensor which relies on the macroscopic Lorentz force calculated taking into account the total field around the particle, i.e., incident and scattered fields:

$$\langle T_{\alpha\beta}\rangle = \frac{1}{2}\mathrm{Re}\left[\varepsilon_0 E_\alpha E_\beta^* + \frac{1}{\mu_0} B_\alpha B_\beta^* - \frac{1}{2}\left(\varepsilon_0 |\mathbf{E}|^2 + \frac{1}{\mu_0}|\mathbf{B}|^2\right)\delta_{\alpha\beta}\right], \quad (2)$$

where $\alpha,\ \beta = x, y, z,$ $\mathbf{E}$ and $\mathbf{B}$ are the electric field and magnetic induction determined on an arbitrary surface Σ enclosing the body, and ε_0 and μ_0 are the permittivity and permeability of vacuum, respectively. The time-averaged electromagnetic force can be obtained as

$$\langle \mathbf{F}_{EM}\rangle = \int_\Sigma \left\langle \hat{T}\left(\mathbf{r}, t\right)\right\rangle \mathbf{n}\left(\mathbf{r}\right) d\sigma, \quad (3)$$

where $\mathbf{n}\left(\mathbf{r}\right)$ is the outward normal to the surface Σ.

To understand physical principles of optomechanical control, let's first consider the time-averaged force in the simplified conditions of a monochromatic illumination and a weakly scattering dipolar particle. This approximation will simplify Eqs. (2), (3) to

$$\langle \mathbf{F}_{EM}\rangle = \frac{\alpha'}{4}\nabla\left\langle|\mathbf{E}|^2\right\rangle + \frac{\alpha''}{2}\left\langle|\mathbf{E}|^2\right\rangle\nabla\varphi, \quad (4)$$

where φ is the field phase and $\alpha = \alpha' + i\alpha''$ is the complex particle's polarizability. The first term in Eq. (4) characterizes the gradient optical force, while the second one represents the radiation pressure. Since the pulling/pushing force is defined by both the field gradient and polarizability signs (Eq. (4)), it can be designed by controlling these two parameters. The field gradient is determined by the spatial distribution of the intensity and dictated by the material environment and the illuminating beam properties (plane wave, Gaussian, Bessel beam etc.). The polarizability of the particle depends on the illumination wavelength, particle's shape and material and it could change its sign at the resonance frequency. Controlling the dimensions and material ingredients of the structure, the resonance frequency can be engineered using various techniques [16–19]. The interplay between the field gradient and polarizabity of the particle can result in either pulling or pushing optical force (Eq. (4)) [20]. It should be noted, however, that this qualitative discussion of the origin of the optical force on the example of a weakly scattering object cannot be directly applied in the case of a strong scatterer in a waveguide, when the electromagnetic field distribution is significantly influenced by the object, and a self-consistent numerical analysis is needed.

To engineer the field gradient required to achieve a pulling optical force, we have considered a single mode SPP waveguide consisting of a V-groove ($\sim 20^\circ$ opening angle, 200 nm depth, 5 nm radius of curvature of sharp corners) made in a semi-infinite silver film. The waveguide was designed for the 532 nm signal wavelength. The V-groove waveguide supports the fundamental low-loss plasmonic mode with the effective index of $n_{\mathrm{SPP}} = 1.29{+}0.012\mathrm{i}$.

The polarizability needed for flexibility in optimization of the spectrum of pulling/pushing force can be obtained using a core-shell spherical particle, which in vacuum is given by [21]

$$\alpha = 4\pi\varepsilon_0 a^3 \frac{(\varepsilon_2 - 1)(\varepsilon_1 + 2\varepsilon_2) + \eta(\varepsilon_1 - \varepsilon_2)(1 + 2\varepsilon_2)}{(\varepsilon_2 + 2)(\varepsilon_1 + 2\varepsilon_2) + \eta(2\varepsilon_2 - 2)(\varepsilon_1 - \varepsilon_2)}, \quad (5)$$

where ε_1 and ε_2 are the complex permittivities of the core and the shell, respectively, and η is the volume fraction occupied by the core. While Eq. (5) is of limited applicability for low loss particles near the resonance, it is applicable for dissipative particles used in this work [22]. It should be noted that a careful engineering of multipole responses of a particle and the use of nondiffracting beams could result in pulling optical forces even when no additional material structures are present in the surroundings [23].

The nanoparticle's LSP resonance has been designed at around 532 nm in the free space (Fig. 2). A desired core-shell particle has 16 nm diameter silver core [24] and 4.5 nm thick TiO_2 shell (refractive index $n_{TiO_2} = 2.97$). The synthesis of similar particles has been studied in detail [25]. It should be noted that when particle is placed inside the waveguide, the LSP resonant frequency is significantly modified due to the interaction between the particle and the metal walls of the waveguide. Moreover, this resonance will depend on the particle position when the particle moves inside the waveguide (Fig. 2). This effect will be taken into account below in numerical calculations of the transmission. The system of a V-groove waveguide and a core-shell particle is flexible enough to ensure that virtually any combination of signal and control operating wavelengths are possible to design on demand.

In order to evaluate the force on the particle, we have performed finite element (FEM) numerical simulations [26] to calculate self-consistent electromagnetic fields and time-averaged optical forces $\langle \mathbf{F}_{EM}\rangle$ using the Maxwell's stress tensor (Eqs. (2), (3)) without any approximations. The control beam size has been assumed much larger than the groove width, so that the plane wave illumination has been considered.

In the absence of control light, the nanoparticle rests at the bottom of the V-groove (insert in Fig. 2b). In the presence of control light, the particle experiences either pulling or pushing force depending on the wavelength with a distinct resonance (Fig. 2b). The force depends also on the position of the particle inside the waveguide. Illumination at the 520 nm wavelength provides strongest pulling force at the bottom of the groove (Fig. 3a,b). It should be mentioned that the resonance of the pulling force is blue-shifted with respect to the particle's LSP. This is because the gradient force depends on the real part of the polarizability (Eq. (4)) which has a minimum where it is negative (pulling optical force) and a maximum at the LSP frequency (Fig. 2a), while the LSP resonance is determined by the maximum of the absolute value of the polarizability). With the intensities of

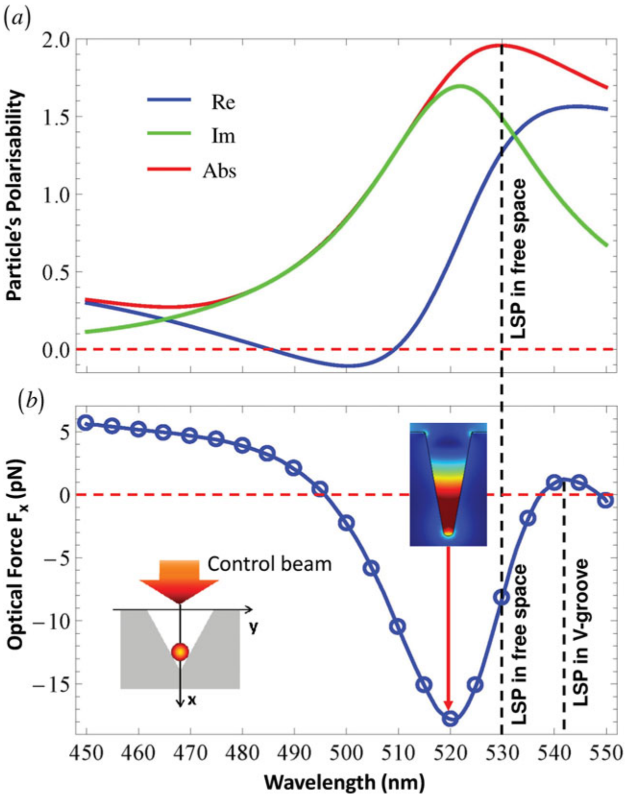

Figure 2 (a) Polarisability of the core-shell particle in free space (real, imaginary parts and absolute value). (b) Spectrum of the optical force (x-component) acting on the core-shell nanoparticle at the bottom of the V-groove silver waveguide. The control light intensity is 250 mW/μm^2. The particle's LSP resonances in free space and at the bottom of the V-groove, shown by the vertical lines, are 530 nm and 543 nm, respectively. The parameters of the nanoparticle and the waveguide are given in the text. Insets show the geometry of the system and the electric field distribution of the control light at the wavelength of 520 nm in the waveguide without the nanoparticle.

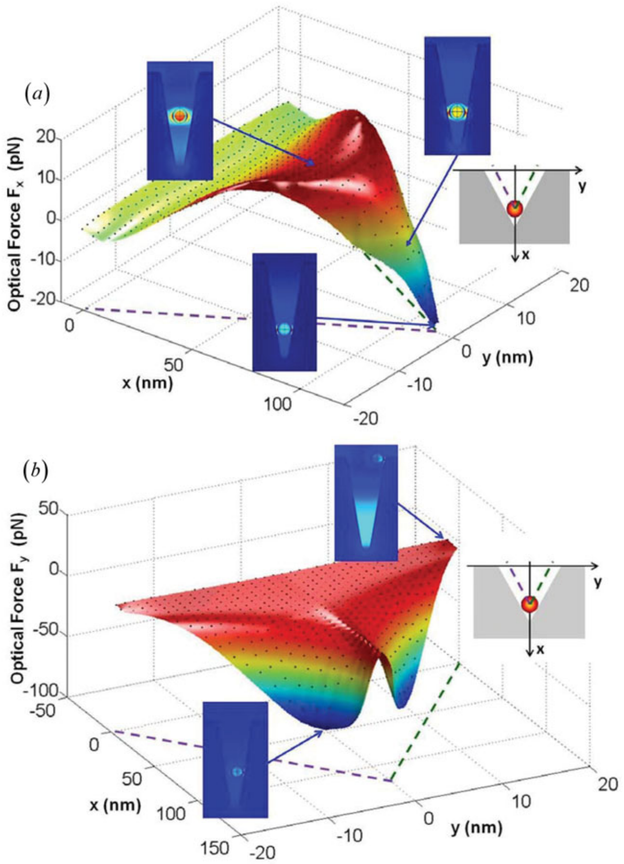

Figure 3 (a) x-component of the optical force as the function of the particle's position inside the V-groove. (b) y-component of the optical force as the function of the particle's position inside the V-groove (please note that in this plot the sign of the force for y < 0 has been changed to simplify presentation: this force is always directed towards the symmetry axis of the waveguide and is positive for y < 0). Insets show the control electric field distribution inside the waveguide for different positions of the particle. All the parameters of the V-groove and the particle are the same as in Fig. 2. Control light wavelength is 520 nm and its intensity is 250 mW/μm^2.

the control light of about 250 mW/μm^2, the pulling force is more than one order of magnitude larger than the Van der Waals force acting on the nanoparticle at the bottom of the V-groove and enough to overcome it and the gravity to lift the particle. Quasi-CW operation regime using nanosecond pulses ($\sim$100 ns and shorter) of the control beam enables to maintain the system below the damage threshold [27,28] and, at the same time, observe the opto-mechanical dynamics, as we will subsequently show.

Due to the field distribution of the control light in the V-groove and variations of the system polarizability with the particle's position, the x-component of the force changes its sign at some point along the symmetry axis of the groove, which determines the equilibrium position of the particle. This equilibrium position does not depend on the intensity of the control light, if it is larger than the threshold required to overcome gravity and van der Waals forces. At the same time, the strong transverse optical force (y-component) prevents the particle from sticking to the side walls of the waveguide. The particle remains in a stable equilibrium relative to the y-axis since the deviation of the particle's position from the $y = 0$ axis leads to a strong returning force, as y-component of the force is always directed towards the symmetry axis of the groove.

5. Dynamical behaviour of the modulator and transmitted signal

The discussed NOM effect allows achieving modulation of the guided light via nanoparticle's auto-oscillations in the waveguide under CW control illumination. The numerical solution of Eq. (1) enables investigations of the particle's time-dependent dynamics in the waveguide and the associated signal light modulation. The predominant field

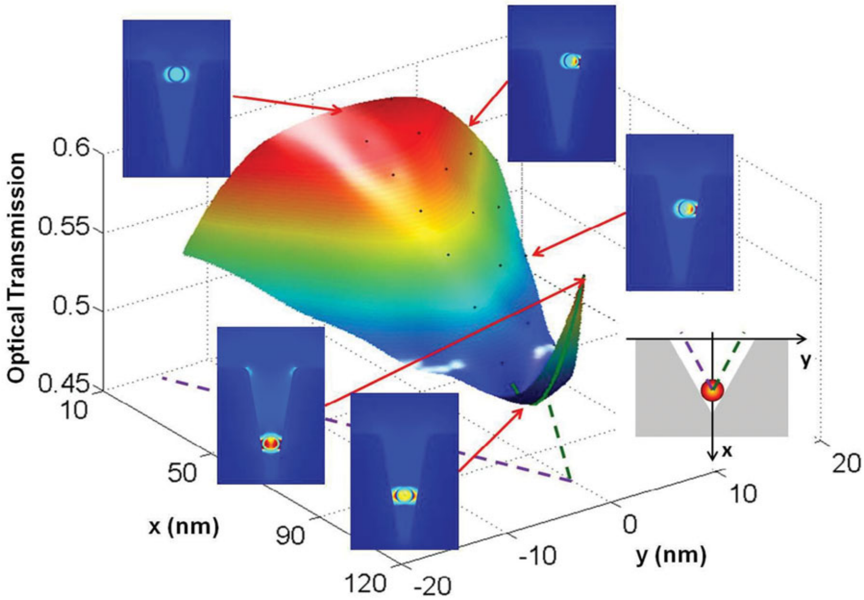

Figure 4 Transmission of the 532 nm waveguided mode as the function of the position of the nanoparticle inside the V-groove. All the parameters are the same as in Fig. 2. The green curve on the surface shows the particle's trajectory in the auto-oscillation regime. The insets show the signal electric field distribution for different positions of the particle inside the V-groove.

component of the waveguided mode at the 532 nm wavelength is parallel to the substrate surface (y-direction), and it will be scattered by the nanoparticle most efficiently. The induced dipole of the particle has the emission diagram in the direction perpendicular to the waveguided mode propagation and scatters it out, leading to the modulation of the modal loss of the waveguide (Fig. 4).

If the intensity of the control light is below the threshold needed to overcome the van der Waals forces, the particle is at rest at the bottom of the waveguide, and the transmission of the waveguide is high (Fig. 4). If the control light intensity exceeds the threshold, the particle moves towards the higher equilibrium point. Since the acceleration depends on the optical force, the higher control light intensity the shorter transient time. The remarkable changes (up to 10%) in the signal intensities could be achieved with only one 25 nm diameter particle. The use of several particles in the waveguide will further increase the modulation depth, as this type of modulation is a cascaded process and has serial action. The most significant changes in the transmission are achieved with the particle's motion close to the bottom part of the V-groove, since the particle has been initially optimized at this condition.

The particle oscillates around the upper equilibrium point with the frequency dependent on the intensity of the control light (the intensity determines the returning force on the particle). Since friction losses in the system are small, these oscillations are practically undamped. The corresponding waveguide transmission variations as the function of time are presented in Fig. 5, showing the oscillatory behaviour due to the particle auto-oscillations. This results in the modulation (pulse-train generation) of the initially CW waveguided signal at the frequency of auto-oscillations. Adjusting the control light intensity, the remarkably high clocking frequency can be achieved in the range 22—40 MHz. The maximum frequency is defined by the system's geometry and limited by the acceleration of the

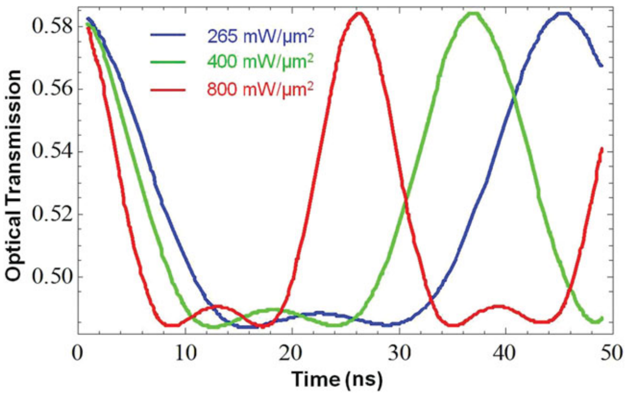

Figure 5 The time-dependent signal transmission in the presence of the continuous control light of different intensities. The particle moves along the trajectory shown in Fig. 4. All other parameters are the same as in Fig. 2.

particle when control light is switched on, which may lead to the ejection of the particle from the waveguide or the optical damage if the intensity of the control light is too strong. Further cascading with the set of nanoparticles oscillating with different phases may be used to increase the modulation frequency. It should also be mentioned that deviations of the waveguide shape from the ideal V-groove will modify the spatial variation of the gradient force and, as the result, the equilibrium point will be modified. Nevertheless, the device performance may be adjusted by tuning the control light intensity. A z-component of the optical force can also show off in a waveguide with imperfections. However, in the waveguide of sufficient length, the stabile point will emerge due to statistical reasons.

It is important to estimate the energy requirements for the proposed opto-mechanical modulation. The energy per bit of the information corresponds to the energy needed to move the particle from the bottom of the V-groove to the equilibrium point at the top of the waveguide and is of the order of 10^{-18} J, much lower than the switching energy of modern electronic transistors. Another important characteristic is the energy dissipation in the metal system which ultimately will lead to the heating of the system and possible undesirable temperature effects. Numerically estimated upper bound of the energy absorption in the particle is about 10^{-20} J for the 300 mW/μm^2 control intensity. Additional absorption in the waveguide may increase the energy dissipation.

6. Conclusion

In conclusion, we have proposed a novel approach for controlling light with light on the nanoscale. The process is mediated by a nanoparticle motion driven by a control beam; the particle scatters the waveguided signal light with the position-dependent efficiency. This concept was employed for a novel NOM modulator which exhibits 10% modulation depth per one nanoparticle and the response time on the nanosecond scale with the record low energy per bit requirement of about 10^{-18} J. The modulation frequency depends on the intensity of the control light and not on its pulsing. The ability of careful engineering of optical forces on the nanoscale makes nanomechanical systems driven by light a new promising technology for optical signal processing.

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