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Dynamics of the optical forces in nanosystems

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Abstract. We investigate optical forces in the time domain, instead of using the time-average Maxwell stress tensor. We demonstrate first that a plane wave causes on a physical object an optical pressure that fluctuates at optical frequency in the time domain. The analytical formula for the optical force dynamics is presented for this case. The case for two-wave illumination with slightly different frequencies is considered next. It is shown that in this case the optical force acquires a component at the beating frequency. The analytical expression for the transient force is deduced and its relation with average force explained in detail.

1 Introduction

Since Kepler's observation of comet tail bending in the 17th century, the electromagnetic forces created by light have raised a tremendous scientific interest. These forces result from the exchange of momentum between photons and physical objects and are conventionally considered as static pulling [1] or pushing [2–5] entities. The electromagnetic wave theory, on the other hand, predicts that the momentum carried by an electromagnetic wave includes both a static and a time-varying component [6]. The oscillating component plays an important role in practical applications when, for example, optical pulses are utilized as incident illumination for trapping experiments [7, 8]. They also become important when an object is illuminated with two frequency-detuned waves at frequencies ω_0 and $\omega_1 = \omega_0 + \Omega$, $\Omega << \omega_0$. The beating effect in this case gives rise to the force at frequency Ω. The appearance of this force is widely explored in optomechanics at the micro-[9] and macro-scales [10]. Furthermore, several very ambitious ideas for controlling the optical force in the temporal domain by utilizing complex-valued frequency excitation have recently arisen [11].

On looking through the literature, we see that various earlier research publications investigated numerically the optical force in the time domain [12, 13], leaving the theoretical analysis of the transient force quite understudied.

We address this challenge by presenting a generic formalism that serves as a framework for the study of the dynamics of optical forces in the time domain for a single wave illumination and for the illumination with two waves.

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2 Analytical expressions for the optical force

2.1 Film under monochromatic planewave illumination

Let us consider a planewave having the wavelength λ_0 and impinging at normal incidence on a film with a thickness d, refractive index n_{film} and immersed in a medium with the refractive index equal to 1, see Fig. 1. The reflection (r_f) and transmission (t_f) coefficients in this case can be related to the normalized thickness of the film $\delta = 2\pi n_{\text{film}} d/\lambda_0$ and the refractive index parameter $\Delta_\pm = n_{\text{film}}^{-1} \pm n_{\text{film}}$ as:

$$r_f = \frac{-0.5i\sin(\delta)\Delta_-}{\cos(\delta) - 0.5i\Delta_+ \sin(\delta)}, \quad (1)$$

$$t_f = \frac{1}{\cos(\delta) - 0.5i\Delta_+ \sin(\delta)}. \quad (2)$$

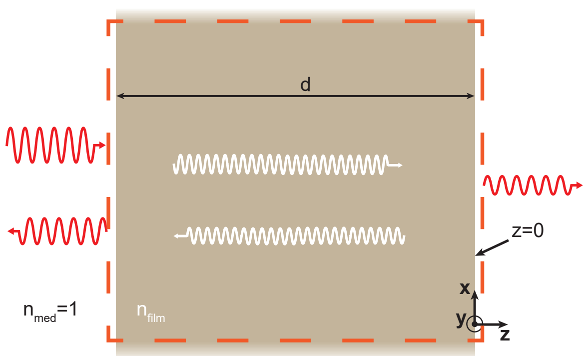

Figure 1. Sketch of an infinite film illuminated with a planewave propagating from left to right. Red dashed box indicates the part of the film, for which the force is calculated.

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By analysing the Maxwell stress tensor [14], the average optical force acting on a film can be found in this case. For a segment of film having the total area $2\Sigma_0$ (front+back facets), the force has the form

$$< \mathbf{F} > = \frac{\Sigma_0}{c}\left(\left(1 + r_f r_f^* - t_f t_f^*\right)\right)\mathbf{z}. \quad (3)$$

Here, c is the speed of light in vacuum and $\mathbf{z}$ is a unit vector in the z-direction. Quite interestingly, the film additionally experiences a transient force that oscillates in time. This can be easily understood by recalling that the Poynting vector $\mathbf{S} = \mathbf{E} \times \mathbf{H}$ acquires an oscillating component under a monochromatic plane wave illumination. Hence, as the result of momentum conservation, an oscillating force appears. The magnitude of this force is also linked to the reflection coefficient of the film and has the following form:

$$|\mathbf{F}(t)| = \frac{\Sigma_0}{c}|2e^{-2i\omega_0 t}r_f|\mathbf{z}. \quad (4)$$

The presented formula gives an analytical relation between the average and transient forces acting on a structure. As can be seen, this force in Eq. (4) oscillates at the frequency ω_0, which is typically in the range of PHz for the optical range and is too high for a mechanical oscillator to develop a noticeable response. Quite interestingly, there is a technique that allows downshifting this frequency to the mechanical oscillation frequency.

2.2 Arbitrary object under two-wave illumination

Let us consider an object illuminated with two plane waves having frequencies ω_0 and $\omega_0 + \Omega$, $\Omega << \omega_0$, as shown in Fig. 2(a). Let us also suggest that the intensities of two waves are equal and the waves are propagating along the same direction ($\theta = 0$). In this case, the average force is twice the force produced by each of two waves $\langle\mathbf{F}\rangle$. The oscillating optical force in this case is also linked to the average force and oscillates as

$$|\mathbf{F}(t)| = 2\langle\mathbf{F}\rangle|\cos(\Omega t)|. \quad (5)$$

As can be noted, the force now oscillates at frequency Ω, that can be set within the kHz range, depending on the value of Ω. The dynamics of the force is presented in Fig. 2(b). It can be clearly noted that the peak force achieved in this case is two times stronger than the average one.

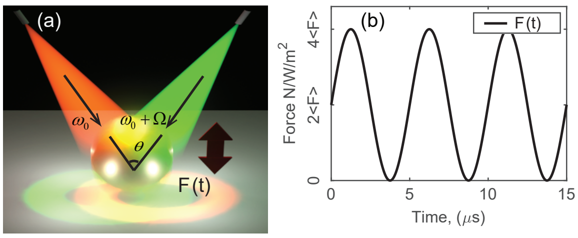

Figure 2. (a) Two optical waves with frequencies ω_0 and $\omega_0 + \Omega$ focus on a particle, generating a beating force at the frequency Ω. (b) The time domain dynamics of the optical force found for two waves of equal intensity and having beating frequency $\Omega/2\pi$ = 200 kHz. Here $< \mathbf{F} >$ denotes the average force generated by each wave.

3 Conclusions

The analytical equations for the optical force in the time domain for a single and two wave illuminations were presented and a link between the average and the transient optical forces was established.

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