Optical Force Control Using Phase-Gradient Metasurfaces

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Abstract – **We propose to control the motion of nanoparticles using phase-gradient metasurfaces. The latter are used to generate surface waves, which put the particles into motion, when illuminated by a normally incident plane wave. We present an initial study of the force and acceleration acting on these particles due to their interactions with the surface wave.**

I. INTRODUCTION

The manipulation of nanoparticles through optical forces has attracted major attention since the first experimental demonstration of optical trapping [1]. Since then, a myriad of techniques have been proposed to transport and trap nanoparticles [2]. In the context of this work, we are mostly interested in the optical forces generated by structured surfaces [3–7] and evanescent fields [8–15]. Our goal is to leverage the amazing field engineering capabilities of metasurfaces to control electromagnetic forces [16]. More specifically, we propose to use phase-gradient (PG) metasurfaces [17, 18] to generate surface waves in order to manipulate nanoparticles. The metasurfaces may be made of several PGs so as to form a path that the particles would have to follow. Moreover, anisotropic PG structures may also be used to control the direction of motion by tuning the polarization of the illumination.

II. OPTICAL FORCE DUE ON A SMALL PARTICLE TO A PHASE-GRADIENT METASURFACE

Let us consider a phase-gradient metasurface lying in the yz-plane at $x = 0$. The phase-gradient exhibits a progressive phase increase in the positive z-direction such that a normally incident plane transforms into a forward-propagating surface wave on top of the metasurface, as depicted in Fig. 1. A small particle, placed at a distance d from the top of the surface, is subjected to electromagnetic forces due to its interactions with the incident wave and the surface wave. In what follows, we concentrate our attention on the time-averaged transverse force, F_z, that acts on the particle due to the presence of the surface wave. We derive an expression for this force based on the assumption that the particle is small compared to the wavelength.
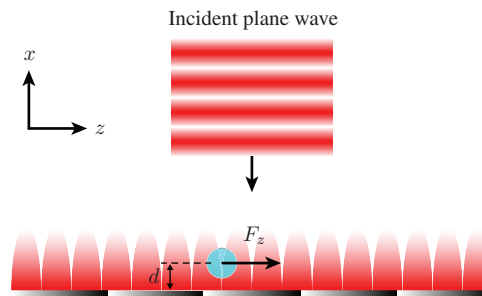

Fig. 1: Small particle being pushed forward due to a surface wave. The latter is produced by the interaction of normally incident plane wave with a phase-gradient metasurface.

In a non-relativistic scenario, the electromagnetic force acting on a given object is found by integrating the divergence of the Maxwell stress tensor over a volume V surrounding that object [19]. Accordingly, the electromagnetic force acting on the object is

$$\langle \boldsymbol{F} \rangle = \int_V \nabla \cdot \langle \overline{\overline{T}}_{\text{em}} \rangle \, dV, \tag{1}$$

where $\overline{\overline{T}}_{\mathrm{em}}$ is the Maxwell stress tensor, which reads

$$\overline{\overline{T}}_{\mathrm{em}} = \boldsymbol{D}\boldsymbol{E} + \boldsymbol{B}\boldsymbol{H} - \frac{1}{2}\boldsymbol{I}(\boldsymbol{D}\cdot\boldsymbol{E} + \boldsymbol{B}\cdot\boldsymbol{H}), \tag{2}$$

and where $\boldsymbol{D}$, $\boldsymbol{B}$, $\boldsymbol{E}$ and $\boldsymbol{H}$ are the total fields in the volume V and $\boldsymbol{I}$ is the identity. In our case, we are interested in computing the force acting on a nanoparticle. We thus assume that the particle is small compared to the wavelength such that its electromagnetic response may be conveniently modeled by a superposition of electric and magnetic dipolar moments. This assumption transforms (1) along with (2) into [20]

$$\langle\boldsymbol{F}\rangle = \frac{1}{2}\mathrm{Re}\left[(\nabla\otimes\boldsymbol{E}_{\mathrm{inc}}{}^{*})\cdot\boldsymbol{p} + (\nabla\otimes\boldsymbol{H}_{\mathrm{inc}}{}^{*})\cdot\boldsymbol{m} - \frac{k_0^4 c_0}{6\pi}(\boldsymbol{p}\times\boldsymbol{m}^{*})\right], \tag{3}$$

where, for a bianisotropic particle, the electric and magnetic moments are respectively given by

$$\begin{pmatrix}\boldsymbol{p}\\\boldsymbol{m}\end{pmatrix} = \begin{pmatrix}\overline{\overline{\alpha}}_{\mathrm{ee}} & \overline{\overline{\alpha}}_{\mathrm{em}}\\ \overline{\overline{\alpha}}_{\mathrm{me}} & \overline{\overline{\alpha}}_{\mathrm{mm}}\end{pmatrix}\cdot\begin{pmatrix}\boldsymbol{E}\\\boldsymbol{H}\end{pmatrix}. \tag{4}$$

In relations (3) and (4), the fields $\boldsymbol{E}$ and $\boldsymbol{H}$ and $\boldsymbol{E}_{\mathrm{inc}}$ and $\boldsymbol{H}_{\mathrm{inc}}$ respectively refer to the total fields and the incident fields only. Let us now consider that the small particle to be moved has a spherical shape and that its dominant dipolar response is of electrical nature. In that case, its response may be modeled by an isotropic electric polarizability such that (4) reduces to $\boldsymbol{p} = \alpha_{\mathrm{ee}}\boldsymbol{E}$ and $\boldsymbol{m} = 0$. For such a kind of small spherical particle, the electric polarizability may be expressed as [21]

$$\alpha_{\mathrm{ee}} = \frac{\alpha_{\mathrm{ee}}^{(0)}}{1 + j\frac{2}{3\epsilon_0}k^3\alpha_{\mathrm{ee}}^{(0)}} \quad\text{with}\quad \alpha_{\mathrm{ee}}^{(0)} = \epsilon_0 r^3\frac{\epsilon_{\mathrm{r}} - 1}{\epsilon_{\mathrm{r}} + 2}, \tag{5}$$

where r is the radius of the particle and ϵ_{r} is its relative permittivity. We now derive the expression of the force due
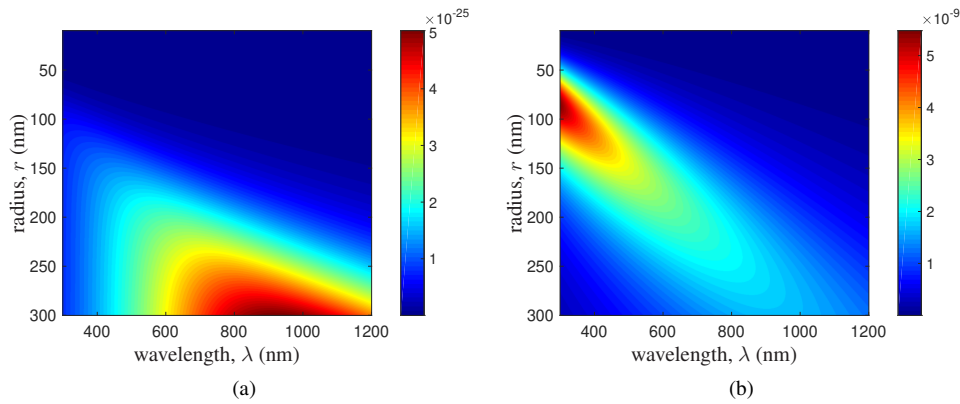

(a)

(b)

Fig. 2: Computed (a) electromagnetic force, F_z, in N and (b) corresponding acceleration of the particle, a_z, in m/s^2. In these two figures, we have used the following parameters: $E_0 = 1$ V/m, $k_z = 1.5k$, $d = 0$ m, $\epsilon_{\mathrm{r}} = 2$ and $\rho = 2650$ kg/m^3.

to the surface wave. We start by defining the electric field of the surface wave, which for p-polarization is given by

$$E_x = E_0\frac{k_z}{k}e^{-\alpha x - jk_z z} \quad\text{and}\quad E_z = E_0\frac{j\alpha}{k}e^{-\alpha x - jk_z z}, \tag{6}$$

where $\alpha = \mathrm{Im}\{\sqrt{k^2 - k_z^2}\}$ and $k_z > k$ since it is a surface wave. Next, we substitute (6) into (3) using (5), which leads to

$$\langle F_z\rangle = \frac{3}{4}\epsilon_0 E_0^2 e^{-2\alpha d}\frac{r^6 k_z k(k_z^2 + \alpha^2)(1 - \epsilon_{\mathrm{r}})^2}{4(9 + k^6 r^6) + 4(9 - 2k^6 r^6)\epsilon_{\mathrm{r}} + (9 + 4k^6 r^6)\epsilon_{\mathrm{r}}^2}, \tag{7}$$

where we have assumed that $\boldsymbol{p} = \alpha_{\mathrm{ee}}\boldsymbol{E} \approx \alpha_{\mathrm{ee}}\boldsymbol{E}_{\mathrm{inc}}$. As expected, the force is oriented in the same direction as that of the propagation of the surface wave. For a given arbitrary set of parameters, we now plot in Fig. 2a the force (7) versus the wavelength and the particle diameter. In Fig. 2b, we plot the acceleration of the particle, which is calculated using $a_z = F_z/m$ and where the mass of the spherical particle of density ρ is $m = 4/3\pi r^3\rho$.

III. Conclusion

This work presents an initial study on the capabilities of phase-gradient metasurfaces to control the motion of nanoparticles. This study reveals several trade-offs that must be considered to successfully achieve this goal. We notably have to consider: the size of the particle with the respect to the wavelength and to the dimension of the metasurface scattering particles, the material constituting the nanoparticles and the strong near-fields produced by the scattering particles which may interfere with the surface wave. We are currently working towards an experimental demonstration whose results will be presented at the conference.

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