Pushing and Pulling Optomechanics with Plasmonic Surface Waves

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Abstract: Light incident on a periodic plasmonic nanostructure is shown to exhibit a pushing or pulling pressure, depending on regulation of the surface wave on the top or bottom, respectively, thereby allowing wavelength control. © 2019 The Author(s)

The radiation pressure measured by Nichols and Hull and also Lebedev confirmed that light can impart a mechanical force on matter [1,2], in a manner consistent with the prediction of J. C. Maxwell [3]. Conventionally, from Maxwell's picture, the maximum optical pressure on a planar surface is $P = 2S/c$ N/m^2, where S is the incident time-averaged power density and c is the speed of light. We proposed [4] and demonstrated [5] that the optical pressure on a nanostructured gold (Au) and silicon nitride (SiN) patterned membrane can substantially exceed that on a planar surface. The physical basis of this enhancement is an asymmetric resonant cavity effect with modest quality factor that provides enhanced fields and increased net pressure under steady state conditions, and this can be established with a 1D cavity result [6]. We now show that regulation of plasmonic surface wave resonances forms a basis to achieve either pushing or pulling of a structure, depending on the structure and incident field variables.

To describe the optical force density inside the material due to the electromagnetic field, we utilize a formulation from Einstein and Laub [7]. The field solution is calculated by a finite element analysis, and then the force density and the corresponding collective normal pressure is obtained. Our focus is an Au film with a periodic array of slots and a dielectric film on the top and/or the bottom, as in Figs. 1 and 2. Such an arrangement could be fabricated on an SiN membrane, as we did previously [5]. In each case, a plane wave is incident from the top with magnetic field out of the page. By regulating the parameters, we show that a dominant surface wave on the top results in a pushing force, and when a strong surface wave is on the bottom of the structure, a pulling force. A strong top or bottom surface wave occurs with transverse resonance, and coupling through to the back with resonance of the metal-insulator-metal slot mode.

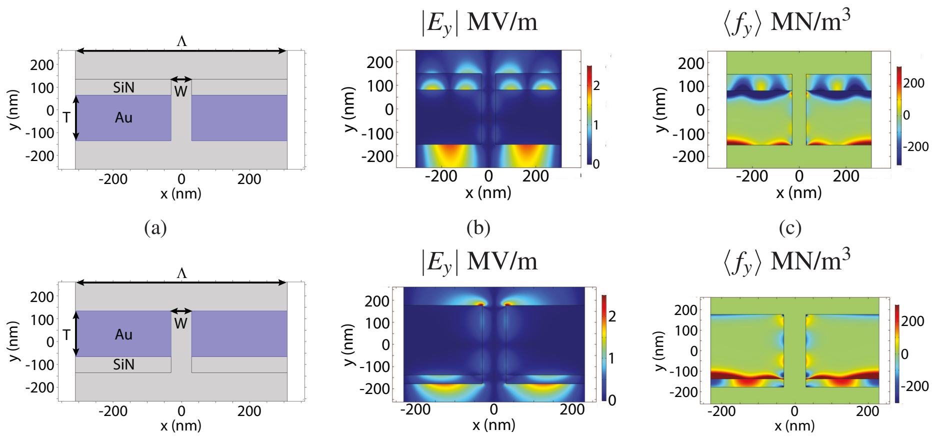
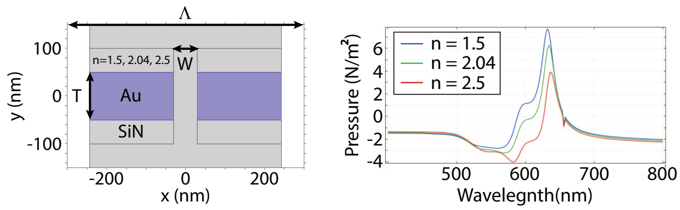


Fig. 1. Simulation of a periodic nanostructured Au membrane with a SiN layer ($n = 2.04$ at 633 nm) added to the top ((a)-(c)) or bottom ((d)-(f)) of an Au film. A 633 nm plane wave is normally incident from the top with magnetic field out of page, and the power density is equivalent to 1 mW over 1 μm radius circle. Parameters: period Λ, slot width W, and Au thickness T, Au dielectric constant $\varepsilon_{Au} = -11.8 + i1.23$ (633 nm). (a) and (d) Simulated structures with an SiN film on the top and bottom, respectively, with (a) period Λ=620 nm, slot width W=60 nm, Au thickness T=232 nm, and SiN thickness 70 nm; and (d) Λ=460 nm, W=60 nm, T=316 nm, and SiN thickness 40 nm. The corresponding y-directed electric field magnitudes are shown in (b) and (e). The y-directed time-averaged force densities are shown in (c) and (f). The top row shows the case of an enhanced pushing pressure of 23.6 N/m^2 and the bottom row a pulling pressure of 11 N/m^2. The pressure magnitude on a perfect mirror with the same intensity is 2.12 N/m^2.

Figures 1(a) and (d) show the simulation setup with an SiN layer added to the top or bottom of an Au membrane,



(a) (b)

Fig. 2. Simulation of wavelength-controlled pushing/pulling pressure on a periodic nanostructured SiN-Au membrane. The illuminating wave condition is the same as in Fig. 1. (a) Simulation setup with parameters: period Λ=460 nm, slot width W=60 nm, Au thickness T=316 nm, top dielectric thickness 10 nm, with refractive indices $n = 1.5, 2.04, 2.5$, and bottom SiN thickness 70 nm. (b) Calculated time-averaged y-directed pressure with the incident wavelength varied from 400 nm to 800 nm: blue, $n = 1.5$; green, $n = 2.04$; red, $n = 2.5$. A positive value indicates a pulling pressure and a negative value a pushing pressure (light is incident from the top in the $-y$-direction). An enhanced pushing pressure is developed around 570 nm and the enhanced pulling pressure in the neighborhood of 630 nm.

respectively. A 633 nm plane wave is normally incident from the top and the intensity is equivalent to 1 mW over a 1 μm radius circle. The top row of Fig. 1 presents the case of an enhanced pushing pressure and the bottom row shows that with an enhanced pulling pressure. Figures 1(b) and (e) show the magnitude of the corresponding y-directed electric fields, dominant in the transverse surface (plasmon) wave. Figures 1(c) and (f) show the calculated time-averaged y-directed (normal component) force density. With the SiN layer on the top (Figs. 1(a)-(c)), we find a pushing pressure of 23.6 N/m^2 (period of Λ=620 nm, Au thickness of T=232 nm, slot width of W=60 nm, and an SiN thickness of 70 nm). From Fig. 1(b), the second resonant mode is promoted on the top surface and the interaction of the field with the Au and the SiN film produces the enhanced pushing force density at the top in Fig. 1(c). For the case with the SiN layer on the bottom (Figs. 1(d)-(f)), we find an enhanced pulling pressure of 11 N/m^2 (Λ=460 nm, W=60 nm, T=316 nm, and an SiN thickness of 40 nm). From Fig. 1(e), we see that the top surface wave is diminished due to the change of the transverse resonance condition (Λ) and Fig. 1(f) shows that the pulling force density on the bottom of the membrane dominates.

We show that the pushing and pulling pressure can be controlled using the same structure by tuning the incident field wavelength. Figure 2(a) shows the simulated structure, where Λ=460 nm, W=60 nm, and T=316 nm. A 10 nm-thick dielectric layer is added to the top with a refractive index of 1.5, 2.04, and 2.5, and the bottom SiN thickness is 40 nm. The illuminating wave condition is the same as in Fig. 1. Figure 2(b) shows the calculated time-averaged normal pressure with an incident wavelength varying from 400 nm to 800 nm for the three different refractive indices of the top dielectric layer. A positive value indicates a pulling pressure while a negative value indicates a pushing pressure (the light is incident from the top and in the $-y$-direction). A pushing pressure occurs with an incident field wavelength around 570 nm and a pulling pressure when the wavelength is in the neighborhood of 630 nm, and for the $n = 2.5$ case (red curve), the pushing and pulling pressure magnitudes are approximately equal at these two wavelengths.

Our results show that simple structures can be designed to be pushed and pulled by light. This phenomenon occurs due to the excitation of field resonances and these can be regulated by design. It is thus possible to regulate both the magnitude and direction of the net optical pressure on a nanostructured material.

References

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