Resonant bending of silicon nanowires by light

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Coupling of two dielectric wires with rectangular cross-section gives rise to bonding and anti-bonding resonances. The latter is featured by extremal narrowing of the resonant width for variation of the aspect ratio of the cross-section and distance between wires when the morphology of the anti-bonding resonant mode approaches to the morphology of the Mie resonant mode of effective circular wire with high azimuthal index. Then plane wave resonant to this anti-bonding resonance gives rise to unprecedented enhancement of the optical forces up to several nano Newtons per micron length of wires. The forces oscillate with angle of incidence of plane wave but always try to repel the wires. If the wires are fixed at the ends the optical forces result in elastic deflection of wires of order 100 nm for wires’s length 50 $\mu$m and the light power 1.5 mW/$\mu$m$^2$.

I. INTRODUCTION

The response of a microscopic dielectric object to a light field can profoundly affect its motion. A classical example of this influence is an optical trap, which can hold a particle in a tightly focused light beam \cite{1}. When two or more particles are present, the multiple scattering between the objects can, under certain conditions, lead to optically bound states. This is often referred to peculiar manifestation of optical forces as optical binding (OB), and it was first observed by Burns et al. on a system of two plastic spheres in water in 1989 \cite{2} and after by other scholars \cite{3, 4, 5}. Optical binding belongs to an interesting type of mechanical light-matter interaction between particles at micro-scale mediated by the light scattered by illuminated particles. Depending on the particle separation, OB leads to attractive or repulsive forces between the particles and, thus, contributes to the formation of stable configurations of particles. The phenomenon of OB can be realized, for example, in dual counter propagating beam configurations \cite{6, 7, 8}.

It is clear that excitation of the resonant modes with high $Q$ factor in dielectric structures by light results in large enhancement of near electromagnetic (EM) fields and respectively in extremely large EM forces proportional to squared EM fields. First, sharp features in the force spectrum, causing mutual attraction or repulsion between successive photonic crystal layers of dielectric spheres under illumination of plane wave has been considered by Antonoyiannakis and Pendry \cite{9}. It was shown that the normal force acting on each layer as well as the total force acting on both layers including the optical binding force follow these resonances. It was revealed that the lower frequency bonding resonance forces push the two layers together and the higher frequency anti-bonding resonance pull them apart. Later these disclosures were reported for coupled photonic crystal slabs \cite{10} and two planar dielectric photonic metamaterials \cite{11} due to existence of resonant states with infinite $Q$ factor (bound states in the continuum (BICs)). Recently Hurtado \textit{et al}. \cite{12} have shown that excitation of quasi BICs in a dimerized high-contrast grating with a compliant bilayer structure stimulates considerable forces capable for structural deformations of the dimer.

However it is remarkable, even two particles can demonstrate extremely high $Q$ resonant modes owing to avoided crossings. The vivid example is avoided crossing of whispering-gallery modes (WGM) in coupled microresonators which results in extremely high $Q$ factor \cite{13, 14}. As a result an enhancement of the OB force around of hundreds of nano Newtons between coupled WGM spherical resonators takes place in applied power 1 mW \cite{13}. After a few years Wiederhecker \textit{et al}. \cite{15} demonstrated a static mechanical deformation of up to 20 nm in double silicon nitride rings of 30 $\mu$m diameter by illumination of milliwatts optical power. In 2005 Povinelli \textit{et al}. \cite{16} calculated forces between two parallel, silicon wires of square cross-section as shown in Fig. I (a) caused by electromagnetic (EM) waves propagating along the wires with frequencies below the light line. Both attractive and repulsive forces, determined by the choice of relative input phase, the forces were found large enough to cause displacements 20 nm of wire with length 30 $\mu$m. However these optical binding (OB) forces are caused by evanescent EM fields which are exponentially weak between the wires that requires a considerable input power 1 mW/$\mu$m$^2$ \cite{16}. In the present letter we consider scattering of plane wave by parallel wires in the resonant regime. Scheme of illumination is shown in Fig. I (a). That demands incident power of only 1.5 mW/$\mu$m$^2$ in order to result considerable deflection of wires of order 100 nm for the wires of length 50 $\mu$m.

We show that for two-parametric variation (the aspect ratio and distance between wires) the system of two wires acquires anti-bonding resonant modes with extremely high $Q$ factor. That happens when a morphology of the anti-bonding resonant mode becomes close to the morphology of the Mie resonant modes with high azimuthal index of effective cylindrical wire. If the plane wave with power 1.5 mW/$\mu$m$^2$ is capable to excite such an anti-bonding resonant mode optical forces reach a value till one nano Newton per micron length of wires. As a result wires of enough length are bending as shown in Fig. I.
The behavior of resonances of isolated nanowire as dependent on aspect ratio of the cross-section $a/b$ was studied by Huang et al.\cite{17} in aim to optimize the $Q$ factor of the nanowire by use the same strategy of avoided crossing as it was used in papers\cite{18,19}. Therefore it is reasonable to start a consideration of optical binding (OB) force of two wires each of them is optimized by the $Q$ factor which reaches maximal amount 2730 for silicon wire with the refractive index 3.48 at $a = b$. The corresponding resonant mode of each wire shown in inset of Fig. 2 has a morphology of the Mie resonant mode with rather high azimuthal index $m = 6$ (close to whispering gallery mode) that explains so small radiation losses. The corresponding optical forces, acting on each wire are shown in Fig. 2. One can see that the OB force tends to repel the wires and reaches a magnitude 70 pico Newtons per micron.

In order to achieve unprecedented $Q$ factor the another strategy was proposed in Ref.\cite{20} based on crossing of the resonances which have opposite symmetry in the isolated wire as shown in Fig. 3(a). However the presence of the second wire lifts this symmetry restriction giving rise to a new series of avoided crossings of resonances. One of such an avoided crossing is shown in Fig. 3(b) with insets showing evolution of the anti-bonding resonant modes. We do not show the bonding resonances because of their undistinguished $Q$ factors. For variation of the distance $L$ between the wires one of the anti-bonding resonant modes of two coupled wires reaches extraordinary small radiation losses. As highlighted in respective inset in Fig. 3(b) at the point of minimal imaginary part the anti-bonding resonant mode of two wires with the cross-section $a = 1.19\mu m, b = 0.592\mu m, a/2b = 1.0152$ and the distance between wires $L = 1.555\mu m$ acquires morphology close to the morphology of effective isolated wire with cylindrical cross-section with $m = 7$ as highlighted by white circle in inset of Fig. 3(b). It is remarkable that the $Q$ factor of this anti-bonding
FIG. 3: (a) Two decoupled TM resonances of opposite symmetry which are crossing for variation of aspect ratio of isolated wire. (b) Evolution of imaginary parts of anti-bonding resonance in traversing with the distance between the wires for $a/2b = 1.0152$. (c) The $Q$ factor vs the distance between the wires and their aspect ratio. $\lambda = 1.55\mu m$ and $a = 0.592\mu m$.

FIG. 4: (a) The optical forces vs distance between wires at the vicinity of the anti-bonding resonance marked in Fig. 3(b) by closed circle $ka/2 = 2.423$, $\theta = 25^\circ$ and $a/2b = 1.0152$. (b) OB force vs the angle of incidence of plane wave $\theta$ at $L/a = 1.5546$ for the power $P_0 = 1.5\text{mW}/\mu \text{m}^2$.

resonance reaches unprecedent value around 15000 at precise tuning of wire’s scales: $a/2b = 1.0152$, $L/b = 1.5546$ as shown in Fig. 3(c). Then one can expect giant OB forces as it was established for two dielectric disks when the frequency of Bessel beams was resonant to the anti-bonding resonance [21]. Indeed Fig. 4 show that the OB force reaches giant values around 4 nano Newtons that exceeds the case shown in Fig. 2 by two orders in value.
FIG. 5: The optical forces vs distance between wires at the vicinity of the anti-bonding resonance marked in Fig. 3. Closed circles show the case when the frequency of incident wave follows to the anti-bonding resonance shown by solid line in Fig. 3 (b). Solid line shows the case when the frequency is fixed \(ka/2 = 2.423, \theta = 25^\circ, a/2b = 1.0152, L/b = 1.555\) that corresponds to maximal \(Q\) factor.

III. DEFLECTION OF WIRES

Following to Povinelli et al.\[16\] we estimate the deflection of wires \(w(z)\) due to optical forces shown in Fig. 4. The deflection obeys the equation

\[
\frac{d^4w_j}{dz^4} = \frac{12f_j}{ab^3E}, \quad j = 1, 2
\]

where \(f_j\) are the optical force acting on unit length of the \(j\)-th wire, and \(E = 169GPa\) is the Young modulus of silicon. In what follows we disregard optical properties of plates to which the wires are fixed assuming their refractive index close to air. For \(|w(z)| \ll S\) and applying the boundary conditions \(w_j(\pm S/2) = 0\) and \(dw_j(\pm S/2)/dz = 0\) one can obtain the solution of Eq. (1)

\[
w_j(z) = \frac{f_j}{ab^3E} \left[ \frac{1}{2} z^4 - \frac{S^2}{4} z^2 + \frac{S^4}{32} \right].
\]

At the specific values \(a = 1.19\mu m, b = 0.592\mu m\) and \(f_j \approx \pm 4200pN\) for the EM power 1.5\(mW/\mu m^2\) we find that maximal deflection at the center between plates \(w(0) = 3.1 \times 10^{-8}S^4\) where the length of wires \(S\) and deflection \(w\) is measured in microns. Therefore for \(S = 50\mu m\) we obtain the maximal deflection is around 150\(nm\) while the EM power of 1\(W/\mu m^2\) propagating along the wires result in deflection 20\(nm\)\[16\] that considerably yields the case of the resonant plane wave illumination with the power by three orders less.

However this estimation of deflection of wires is to be considered as upper limit. As soon as the wires start to bend the anti-bonding resonance with extremely high \(Q\) factor established for two parallel wires will go away from extremal point shown in Fig. 3 (b) by, at least, two reasons. The first reason is related to deviation from optimal distance between the wires. As a result the optical forces will be strongly decreased as shown in Fig. 5. The second reason which also affects the optical forces is related to the bending of wires which put the problem into the 3d one.

IV. FUNDING

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V. DISCLOSURES

The authors declare no conflicts of interest.

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