Chiral meta-atoms rotated by light

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(Received 17 May 2012; accepted 2 July 2012; published online 17 July 2012)

We study the opto-mechanical properties of coupled chiral meta-atoms based on a pair of twisted split-ring resonators. By using a simple analytical model in conjunction with the Maxwell stress tensor, we capture insight into the mechanism and find that this structure can be used as a general prototype of subwavelength light-driven actuators over a wide range of frequencies. This coupled structure can provide a strong and tunable torque, and can support different opto-mechanical modes, including uniform rotation, periodically variable rotation and damped oscillations. Our results suggest that chiral meta-atoms are good candidates for creating sub-wavelength motors or wrenches controlled by light. © 2012 American Institute of Physics.

[http://dx.doi.org/10.1063/1.4737441]
The effective dipole length is given by the near-field interaction terms. Note that the effective capacitance and inductance, as well as the mode amplitudes can be related to the effective voltage applied to the SRRs by the incident field, and the mutual interaction terms. Thus, the above two equations clearly demonstrate that the total torque is actually composed of two parts. One is a rotation angle-dependent torque \( M_\phi(\Phi) \), whose sign is periodically changing as the structure rotates, and thus it leads to the oscillatory dynamics. The component \( M_\phi \) does not depend on \( \Phi \) and it contributes to a continuous rotation. We further note that \( M_\phi \) vanishes when any of the following three go to zero: the mutual interaction \( F_m \), the retardation \( \varphi \) or the twist angle \( \theta \), which verifies its relation with the structural chirality. It can be expected that there will be a RFB when \( M_\text{diff} = |M_\phi| - \max(|M_{\phi,0}|) > 0 \), in which the TSRRP will be driven to rotate continuously in one direction.

To verify our prediction, we compare the results from full wave simulation (CST Microwave Studio). In the analytical model, we choose \( r_a = 1.16 \, \text{mm} \) and \( \theta_0 = 11^\circ \). In the full wave simulation, we calculate the structures that work in microwave and optical frequencies, respectively. For the microwave sample, the metal is gold described by the Drude model \((\sigma = 5.8 \times 10^7 \, \text{S/m})\) and the background is vacuum; while for the optical sample, the metal is gold described by the Drude model \((\epsilon_\infty = 1, \omega_p = 1.37 \times 10^{16} \, \text{rad/s}, \Gamma = 1.2 \times 10^{14} \, \text{Hz})\) and the background is set as SiO2\((r_\epsilon = 2.13)\). The external torque is calculated via the Maxwell stress tensor. Since any linear-polarization can be decomposed into two orthogonal components, we calculate the torque under \( \Phi = 0^\circ \) and \( 90^\circ \), to confirm the position of the RFBs.
Remarkably, for the microwave sample, both the trends of the normalized mode amplitudes and the torques show good overall agreement with our simple model, as shown in Figs. 2(a)–2(d). The differences might arise from the actual geometries of the structures and some perturbation of the charge and current distributions due to strong near-field interaction. For the optical sample [Figs. 2(e) and 2(f)], the simple model (not shown) gives only qualitative agreement, due to the neglect of the metal dispersion. However, the numerical results confirm that the physics is the same for the microwave and optical regimes.

The values in Figs. 2(b) and 2(d) are normalized to an input power density of 1 mW/mm²; in Fig. 2(f), the values are normalized to a power density of 1 mW/μm². The two resonances around 19.6 GHz (205 THz) and 20.8 GHz (250 THz) correspond to the symmetric mode and antisymmetric mode, respectively. We note from Figs. 2(b), 2(d), and 2(f) that there are two RFBs around the resonances, which are denoted by the blue and red shadings: in the blue area (the lower frequency bands), \( M_{\text{ext}} \) is always negative; while in the red area (the higher frequency bands), \( M_{\text{ext}} \) is always positive. Such agreement demonstrates that the simple analytical model of the TSRRP can be used for calculating and designing subwavelength light-driven actuators over a wide range of frequencies. Moreover, it is quite inspiring that the torque calculated from the unoptimized subwavelength (≈2.7/500) optical sample is of the order of \( 2 \times 10^{-20} \) N m, which is comparable to that shown in previous works which use much larger dielectric chiral structures (>25\( \lambda^2 \)) and higher power trapping beams.\(^\text{13} \)

In contrast to the optical motor based on a single resonator, the TSRRP enables us to tune its resonant properties and opto-mechanical behaviour, by changing the geometry of the resonators. To capture insight into the evolution of the RFBs as the twist angle \( \theta \) and the separation \( s \) change, we plot \( M_{\text{diff}} > 0 \) as a function of frequency and \( \theta \) in Figs. 3(a) and 3(b) by fixing \( s = 1 \) mm and \( s = 2 \) mm; in Figs. 3(c) and 3(d), \( s \) varies from 0.5 mm to 3.5 mm, while \( \theta \) is fixed at 45° and 90°, respectively. The regimes with \( M_{\text{diff}} > 0 \) correspond to the RFBs. Through the tuning, we can change the bandwidths, spectral distance and the strength of the two bands.

When carefully examining the evolution of the RFBs, one feature attracts our attention: although the RFBs centre around the two branches of resonances, the variation of their bandwidths and the rotating power does not coincide with the change of the resonances. For the TSRRP we study, the bandwidth of the symmetric mode exhibits a monotonic decrease as the twist angle or separation increases, while a reversed trend can be observed for the antisymmetric mode.\(^\text{18} \) However, the bandwidths of RFBs show a more complicated non-monotonic behaviour since it is affected by several factors. For a given twist angle or separation, there is an optimum configuration in which we can get the strongest rotational power, as shown by the white arrows in Fig. 3. Qualitatively, we can understand this behaviour from Eq. (10): the strength of \( M_{\text{r}} \) is simultaneously affected by the mutual interaction \( F_{\text{m}} \), the retardation \( \phi \) and the twist angle \( \theta \). To take the antisymmetric mode as an example, decreasing the separation or twist angle usually gives a stronger resonance, however, this comes at the expense of smaller

![FIG. 2. Normalized mode amplitudes \( Q_1, Q_2 \) and the radiation torque \( M_{\text{ext}} \) of the TSRRP with \( \theta = 90^\circ \), where (a) and (b) are calculated from the analytical model, (c) and (d) are the full wave calculations of the microwave sample, and (e) and (f) are the full wave calculations of the optical sample. For the analytical model, \( r_a = 1.16 \) mm, \( t_a = 11^\circ \); for the microwave sample, \( r_a = 1.2 \) mm, metal thickness \( t = 0.03 \) mm, \( w = 0.24 \) mm, \( g = 0.2 \) mm, and \( s = 2 \) mm; for the optical sample, \( r_a = 80 \) nm, \( t = 30 \) nm, \( w = 30 \) nm, \( g = 30 \) nm, and \( s = 80 \) nm. The blue and red shadings in the torque diagrams denote the RFBs.](Image 223x268 to 243x336)

![FIG. 3. The frequency bands of continuous rotation as a function of \( \theta \) and \( s \), determined from the condition \( M_{\text{diff}} > 0 \). (a) \( s = 1 \) mm, (b) \( s = 2 \) mm, (c) \( \theta = 45^\circ \), and (d) \( \theta = 90^\circ \). The white arrows indicate the optimum points.](Image 346x212 to 427x308)
values of \( \sin \theta \) and \( \sin \Phi \), thus the optimum configuration should be a balance of the resonance strength, the degree of asymmetry and the retardation.

Using the analytical expression for the torque, we study the dynamics of the structure also taking into account friction in the system, which can be caused by the medium in which the meta-atom is placed. Here, we suppose the TSRRP is fixed in a solid disk with radius \( R = 2 \) mm, and the whole structure is suspended in air. The angular speed \( \Omega = \dot{\Phi}(t) \) of the TSRRP can be found from the dynamic equation using, e.g., numerical Runge-Kutta method

\[
I \ddot{\Phi} + \gamma \dot{\Phi} = M_{ext}(\Phi),
\]

where \( I \) is the moment of inertia of the structure, \( \gamma = \pi R^2 \eta / (4R/3 + 2 \xi) \) is the damping coefficient, which for the case of air viscosity \( \eta = 17.8 \) Pa·s. The introduction of additional friction may change the rotational velocity, but will not change the overall dynamic characteristics. Fig. 4 depicts the torque components \( M_r \) and \( \max(|M_{\ell}|) \) as well as the rotation dynamics of the TSRRP with parameters corresponding to Figs. 2(a) and 2(b), and the incident power flow is 10 mW/mm\(^2\). As expected, two RFBs with opposite rotation directions appear near the symmetric and antisymmetric resonances, with their regimes determined by \( |M_r| > \max(|M_{\ell}|) \), as predicted in Fig. 2(b).

The TSRRP will experience a continuous rotation when driven by a frequency within the RFBs, and thus it can act as a subwavelength motor; while outside the RFBs, the rotation angle becomes stable after a relaxation process, and the structure behaves as an anisotropic scatter and can function as an optical wrench. The scattered wave amplitude also changes periodically as the structure rotates, and thus it provides the possibility to detect its motion and the torque. In contrast to chiral structures with high degree of rotational symmetry or simple anisotropic structures, the TSRRP can offer a variety of opto-mechanical modes: (1) rotation with constant speed, which can be obtained around the point \( \max(|M_r|) \rightarrow 0 \); (2) rotation with time-varying speed (which means one can accelerate and decelerate the structure repeatedly), with its variation periods determined by the frequency; (3) damped oscillations, in which one can control the equilibrium position by changing the input polarization angle or the frequency. Such multifunctional subwavelength light-driven actuator can potentially find a variety of applications in nano-fluidics and nano-robotics.

To conclude, we propose to use a pair of twisted SRRs as an efficient subwavelength optical actuator. By using a simple analytical model and full wave numerical simulations, we studied its mechanism and showed that this structure can be used as a general design prototype in a wide frequency range from microwaves to optics. Such a coupled structure provides strong rotational power and multiple opto-mechanical modes, which can be more easily tuned by incident frequency than other structures like metallic gammadions, and thus benefiting its application in a variety of fields.

The authors thank Miss Y. Sun for the fruitful discussion on the Maxwell stress tensor. This work is supported by the Australian Research Council.

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