8.º Congresso do Comité Português da URSI
Lisboa 28/11/2014

Optical Tractor Beam with Chiral Light

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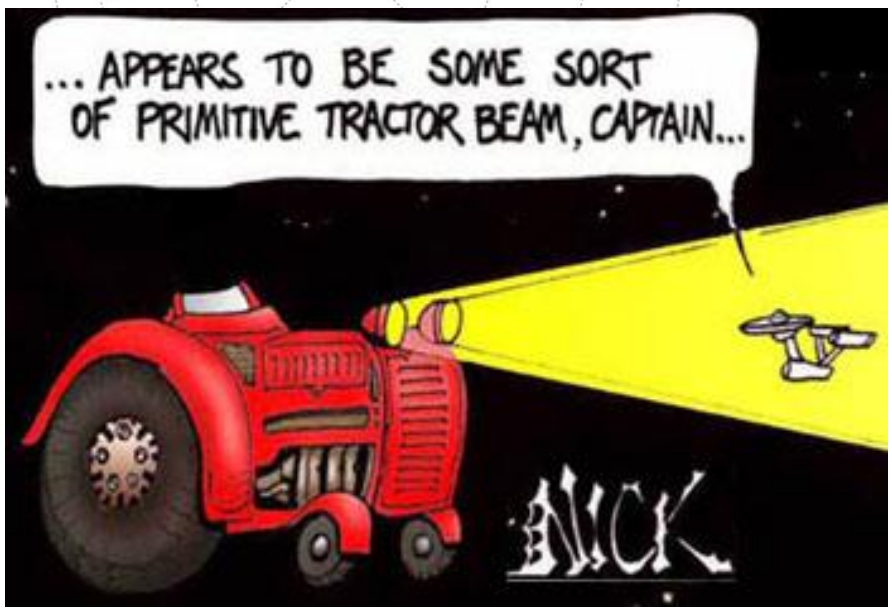
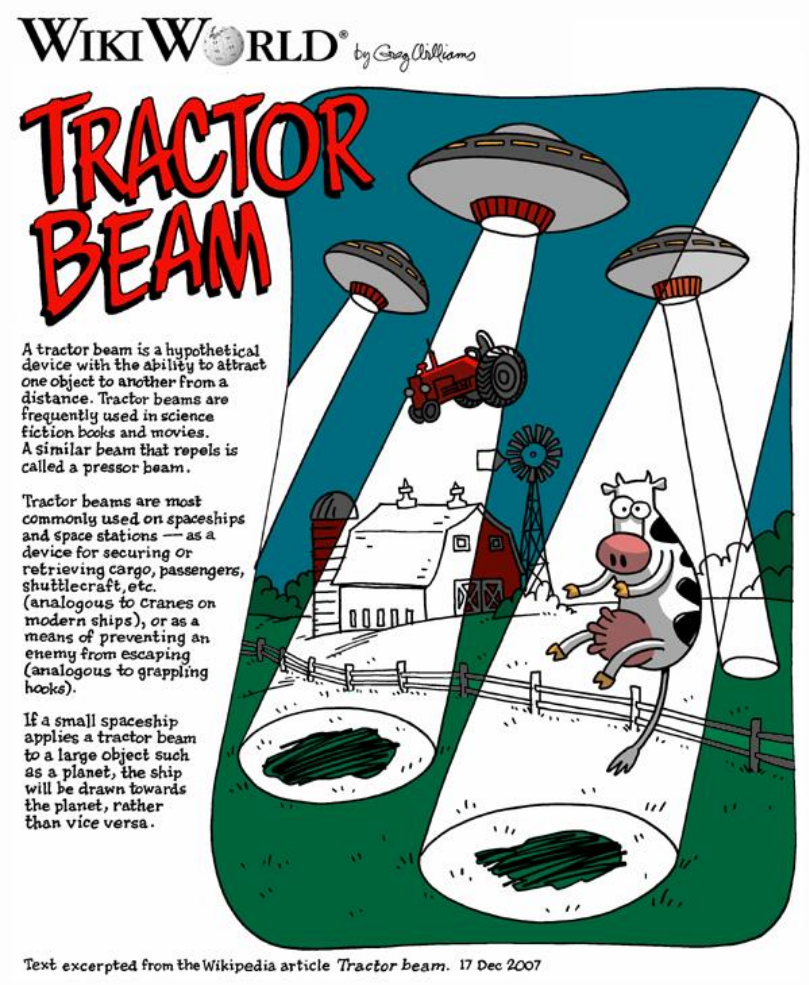
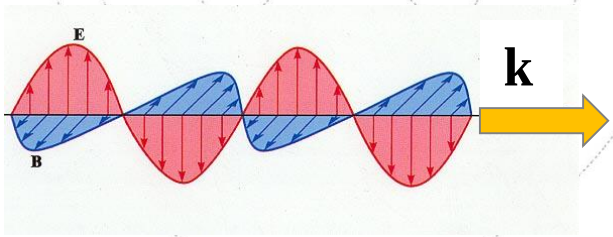
Tractor beam: Science fiction?

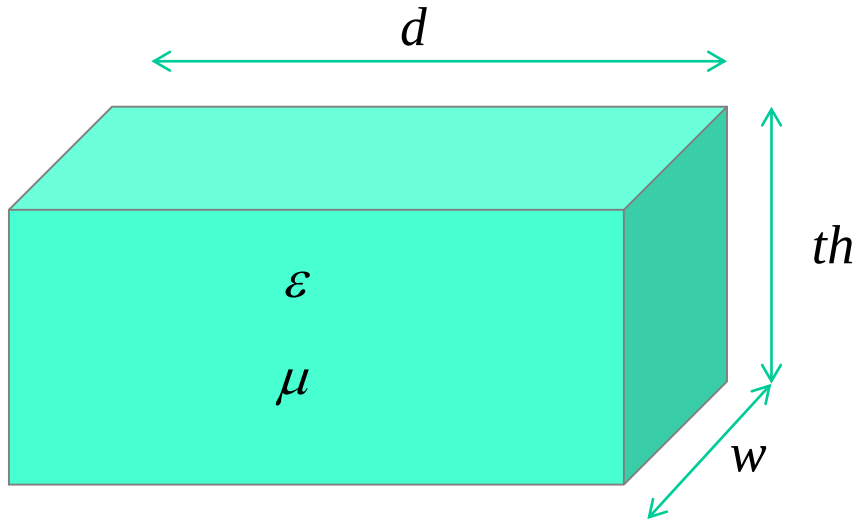




Light Pressure

- **Pressure on a polarizable body illuminated by a plane wave**





$$A = w \times th$$

$$\frac{F}{A} = p = W_{tot,\mathrm{av}}\left(1 + \left|R_L\right|^2 - \left|T_{LR}\right|^2\right) \geq 0 \qquad W_{tot,\mathrm{av}} = \frac{1}{4}\left(\varepsilon_0 \left|E\right|^2 + \mu_0 \left|H\right|^2\right)$$

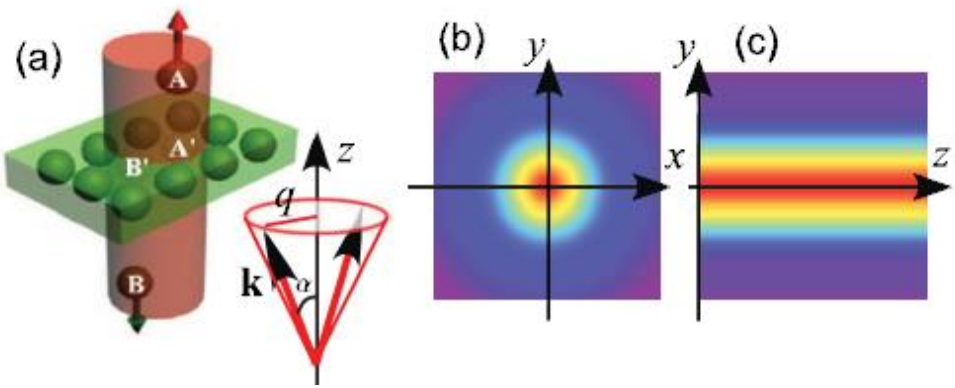
- **The force F is positive and the body is pushed towards the direction of propagation.**

Can light act as a tractor beam?

Tractor beam – Previous research

Single Gradientless Light Beam Drags Particles as Tractor Beams

Andrey Novitsky,[1] Cheng-Wei Qiu,[2,*] and Haifeng Wang[3]

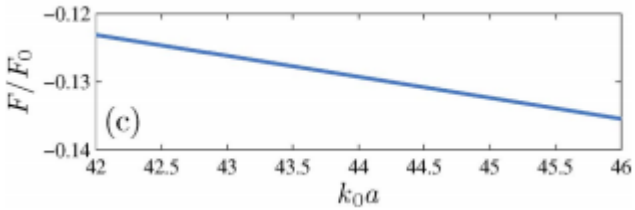


Using tailored (Bessel) light beams it was shown that an object can be pulled towards the direction of the light source

Negative radiation pressure on gain medium structures

Amit Mizrahi* and Yeshaiahu Fainman

October 15, 2010 / Vol. 35, No. 20 / OPTICS LETTERS



Media with gain

$$\frac{F}{A} = p = W_{tot,\mathrm{av}}\left(1+\left|R_L\right|^2 - \left|T_{LR}\right|^2\right)$$

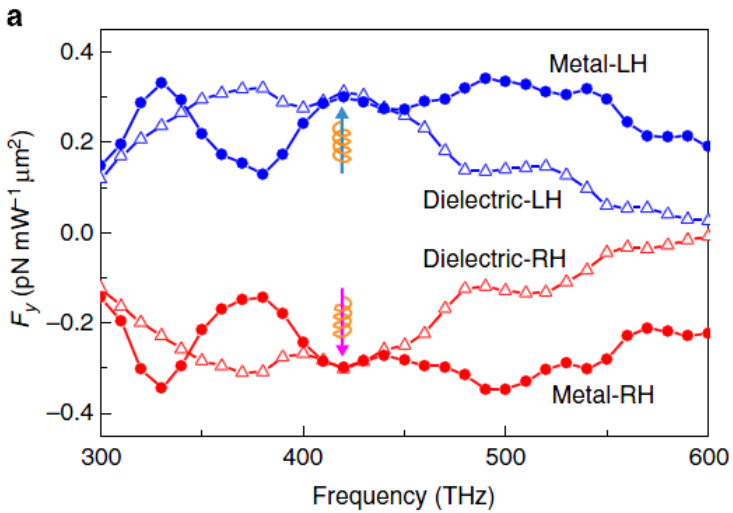
$$\left|T_{LR}\right|^2 > 1$$

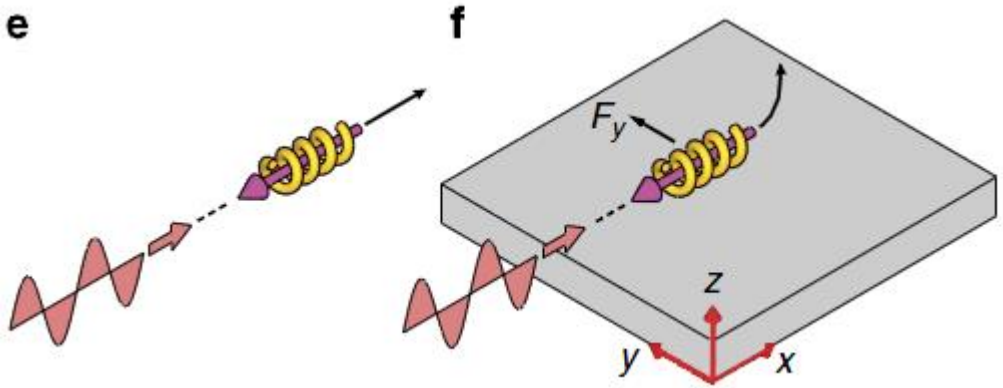
Tractor beam – Previous research contd.

- **It is possible to obtain anomalous light pressure using chiral metamaterials.**

Lateral optical force on chiral particles near a surface

S.B. Wang[1] & C.T. Chan[1]

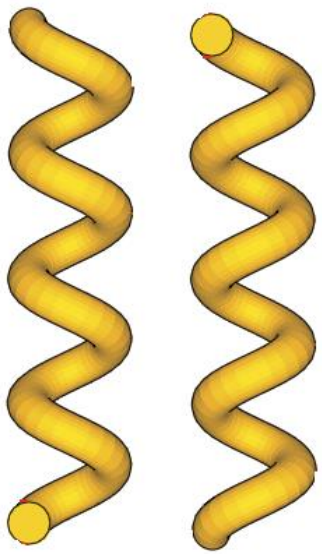




Tractor beam with chiral metamaterials

Chiral media

- **Made of particles that cannot be superimposed on their mirror images.**



Constitutive relations

$$\mathbf{D} = \varepsilon \mathbf{E} + i\chi\sqrt{\varepsilon_0 \mu_0}\,\mathbf{H} \qquad \mathbf{B} = \mu \mathbf{H} - i\chi\sqrt{\varepsilon_0 \mu_0}\,\mathbf{E}$$

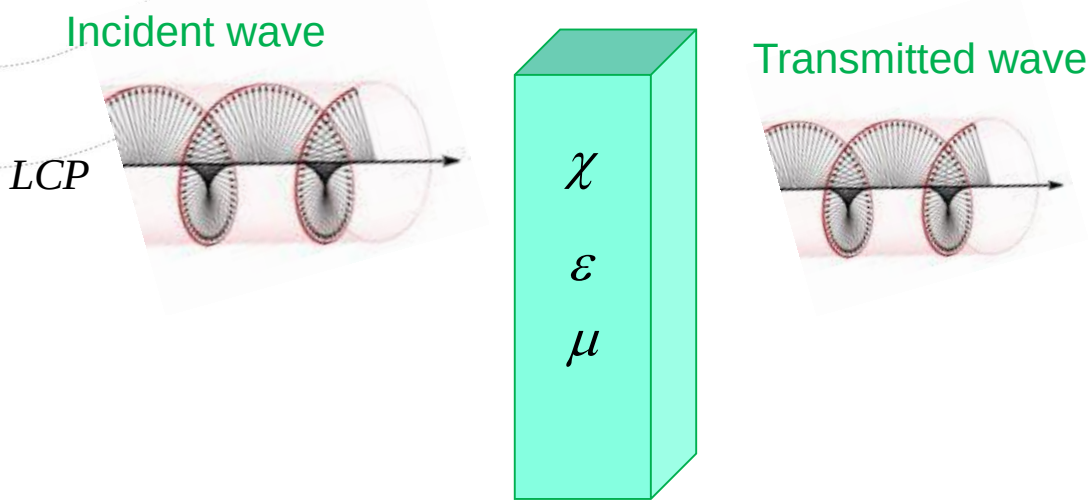
$\chi \longrightarrow$ **Chirality parameter**

Eigenstates are RCP(+) and LCP(-) waves characterized by the refractive index:

$$n_{\pm} = n \pm \chi$$

Scattering of light by a chiral slab

What if an LCP polarized incident wave is completely transmitted across the chiral slab?



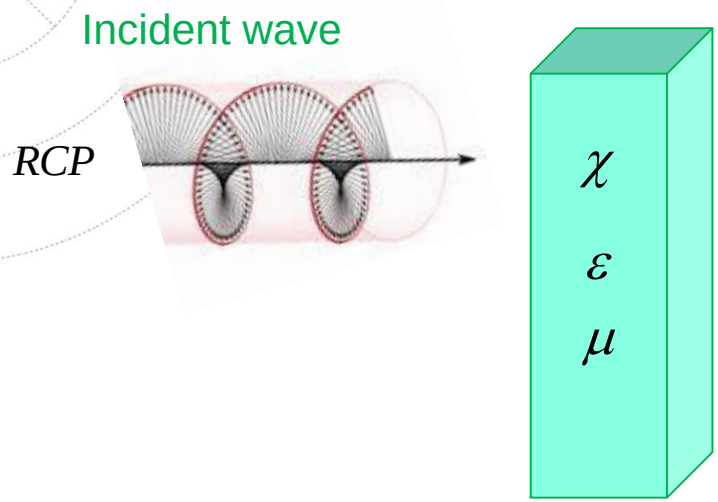
$$p = W_{tot,\mathrm{av}}\left(1+\left|\cancel{R_L}\right|^2-\left|T_{LR}\right|^2\right)=0$$

$$=1$$

- **The wave does not interact with the medium.**

Scattering of light by a chiral slab – contd.

What if an RCP polarized incident wave is completely absorbed in the chiral slab?



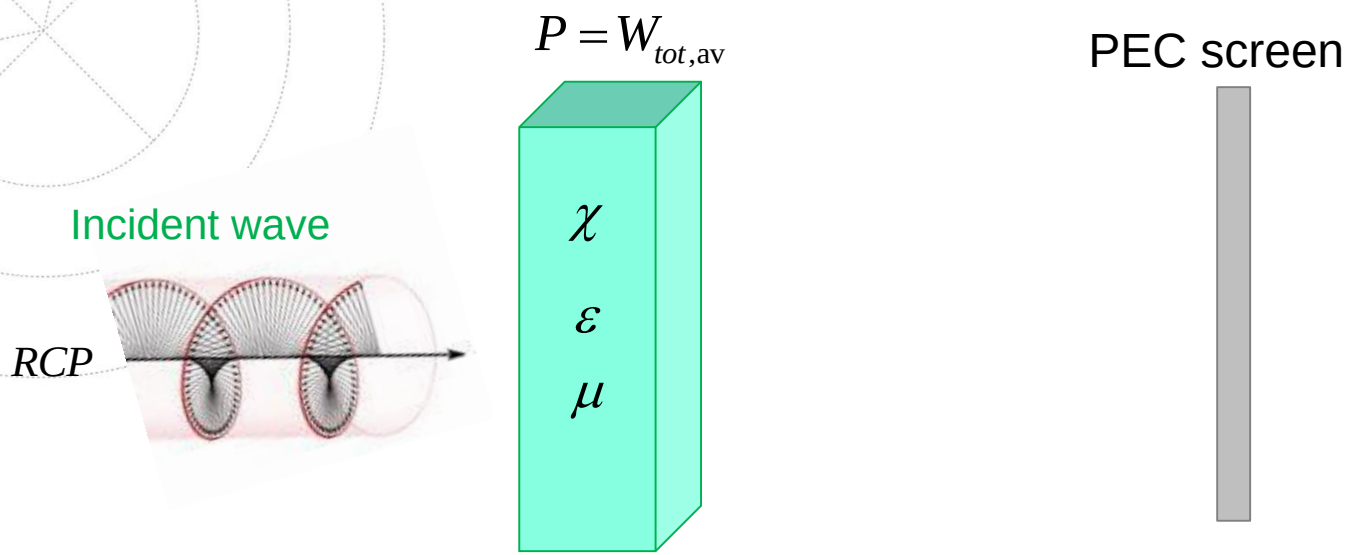
Pressure is positive

The medium is pushed towards the direction of propagation

$$p = W_{tot,\mathrm{av}}\left(1+\left|\cancel{R}_L\right|^2-\left|\cancel{T}_{LR}\right|^2\right)=W_{tot,\mathrm{av}}$$

Our solution

- ***Can we take advantage of the distinct responses of the medium? What happens when a mirror is placed in front of the chiral metamaterial?***

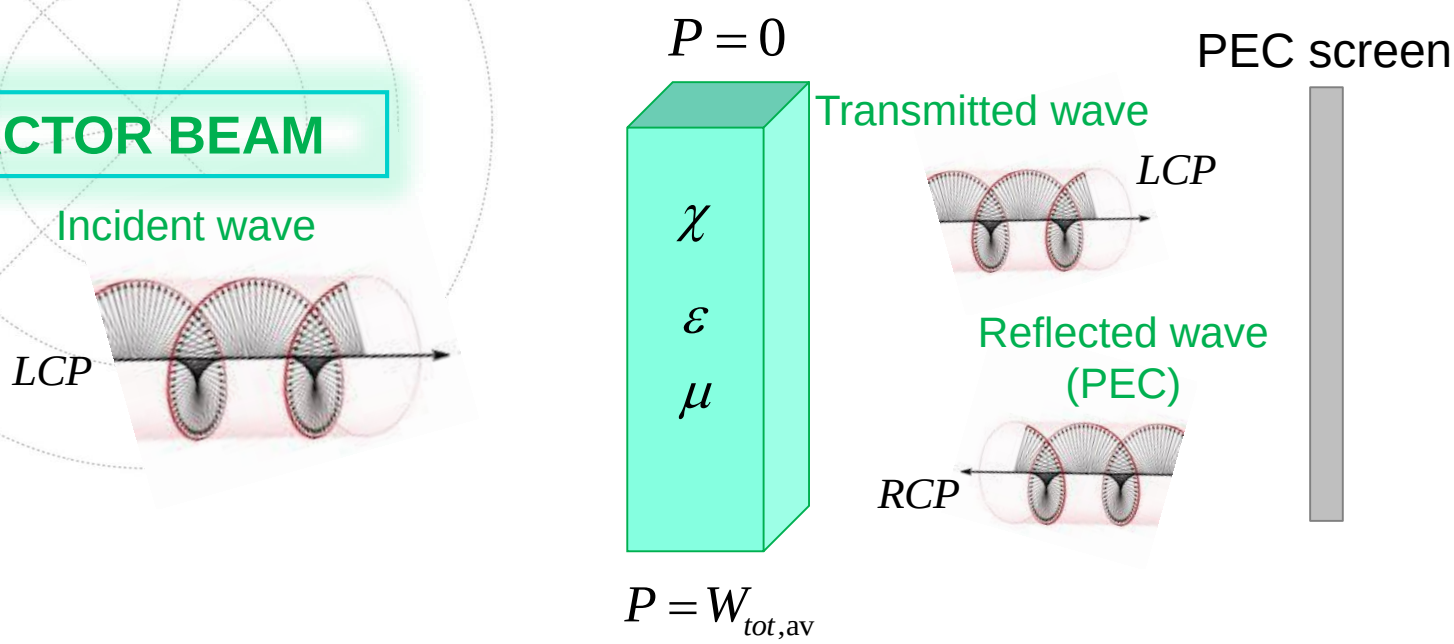


- **Total absorption → The medium is pushed towards the direction of propagation of the incident wave (towards the PEC screen).**

Our solution – contd.

The incident wave actually pulls the chiral metamaterial!

TRACTOR BEAM



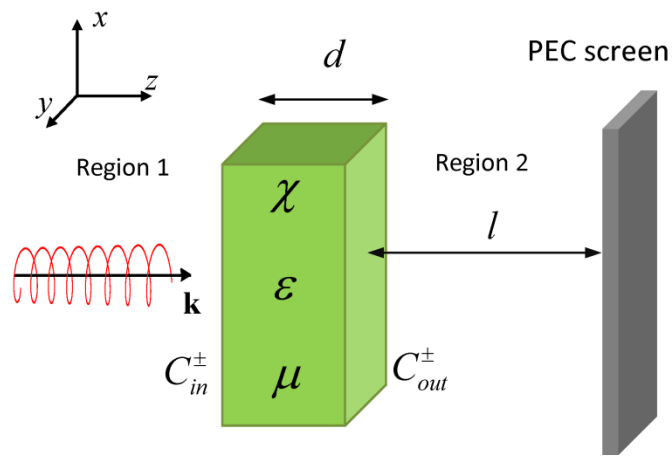
- **Total transmission → The wave does not interact with the medium.**
- **Total absorption → The medium is pushed towards the direction of propagation of the reflected wave**

Conditions to have a tractor beam

The force acting on the slab of chiral metamaterial:

$$\frac{F_{z.\mathrm{av}}}{A} = W_{\mathrm{av}}^{inc}\left(1+\left|\cancel{R}-\frac{e^{i2k_0 l}T_{21}\cancel{T_{12}}}{1+\cancel{R}e^{i2k_0 l}}\right|^2 - 2\left|\frac{T_{21}}{1+\cancel{R}e^{i2k_0 l}}\right|^2\right)$$

$$W_{\mathrm{av}}^{inc} = \frac{\varepsilon_0}{2}\left|C_{in}^{+}\right|^2$$



Goals:

No reflection

Total absorption of the wave coming from the PEC screen.

$$\frac{F_{z.\mathrm{av}}}{A} = W_{\mathrm{av}}^{inc}\left(1-2\left|T_{21}\right|^2\right)$$

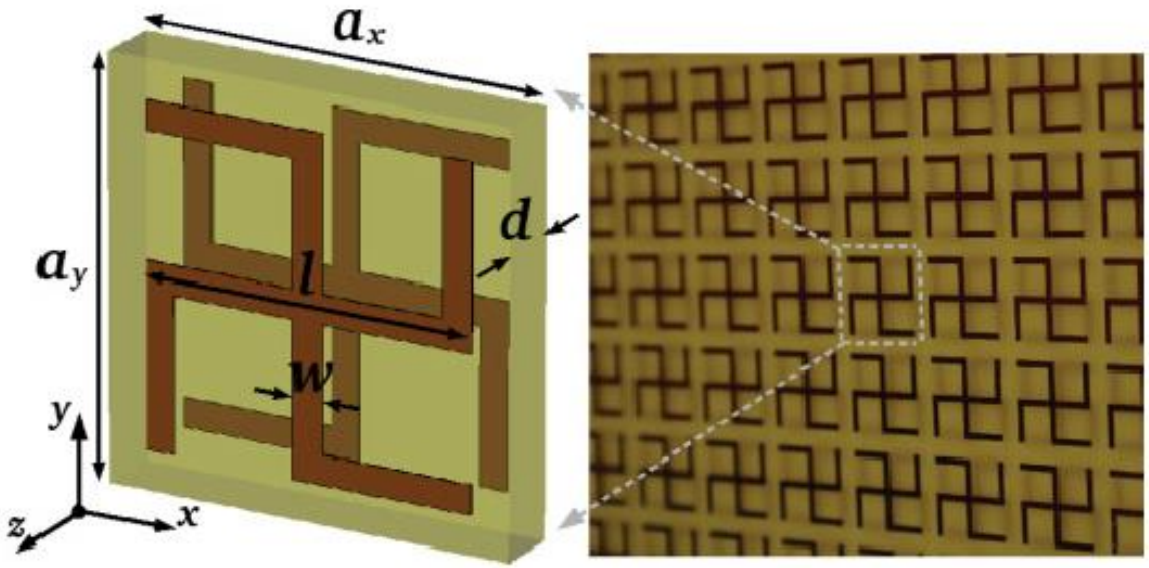
Metamaterial design

Chiral metamaterial – Conjugated Gammadion

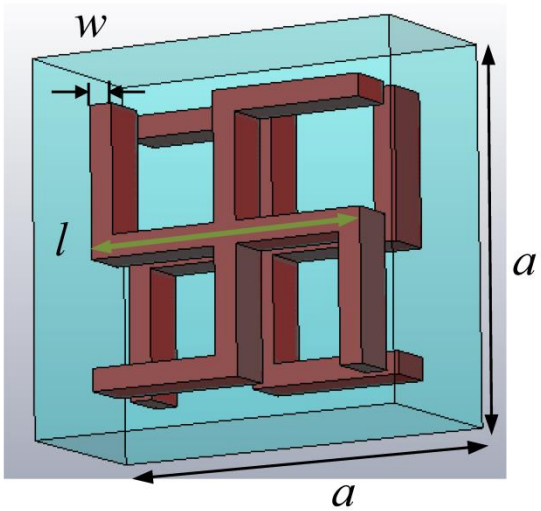
- **Planar chiral metamaterial**

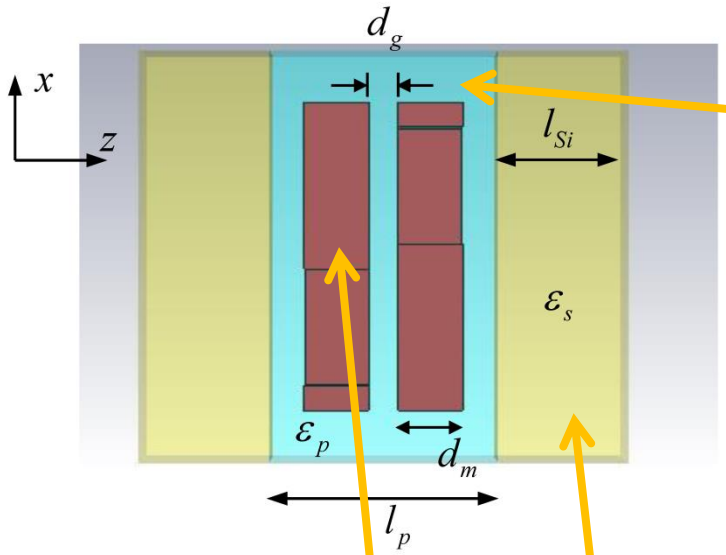
PHYSICAL REVIEW B **83**, 035105 (2011)

Conjugated gammadion chiral metamaterial with uniaxial optical activity and negative refractive index



Structural parameters





Polymide

$$\frac{\varepsilon_p}{\varepsilon_0} = 6.25(1 + i0.03)$$

$l = 151.81\,\text{nm}$ $\quad l_{Si} = 50.6\,\text{nm}$ $\quad l_p = 88.4\text{nm}$

$w = 12.19\,\text{nm}$ $\quad d_g = 11.58\,\text{nm}$ $\quad d_m = 25\,\text{nm}$

Silicon

$$\varepsilon_s / \varepsilon_0 = 11.9(1 + i0.004)$$

$$a = 202.41\,\text{nm} \approx 0.131\lambda_0$$

$$d = 2l_{Si} + l_p = 189.6\,\text{nm} \approx 0.122\lambda_0$$

Silver $\varepsilon_m(\omega) = \varepsilon_0\left(1 - \frac{\omega_m^2}{\omega^2 + i\omega\Gamma}\right)$ $\quad \omega_m/2\pi = 2175\,\text{THz}$ $\quad \Gamma/2\pi = 4.35\,\text{THz}$

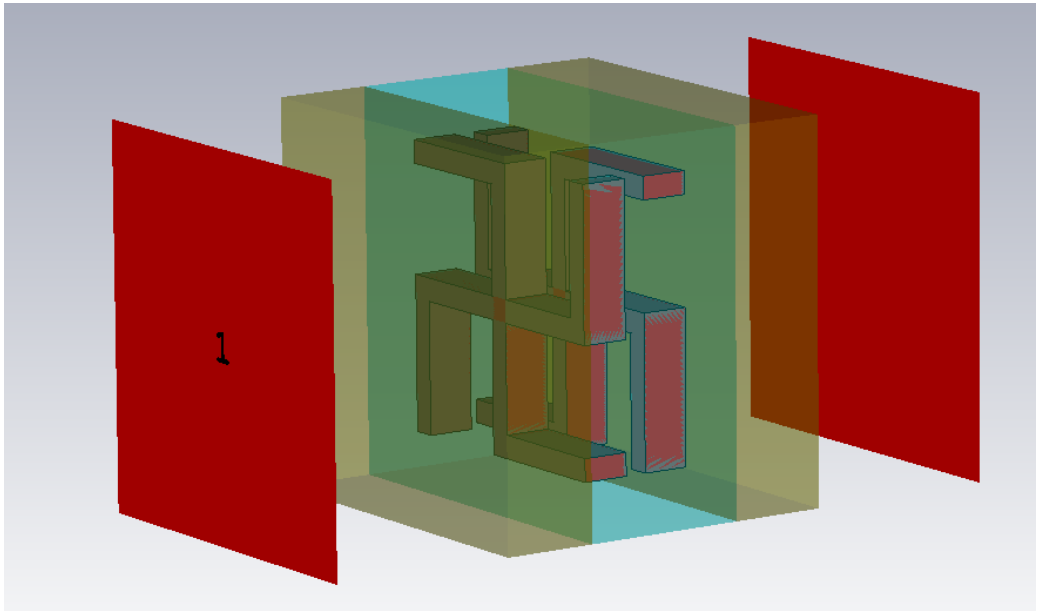
- ***Operating wavelength*** $\lambda_0 = 1550\,\text{nm}$

$$f_0 = 193.548\,\text{THz}$$

Numerical modelling

Frequency Solver

- Periodic boundaries
- Two ports with two modes:
  1. Electric field oriented along x-direction.
  2. Electric field oriented along y-direction.



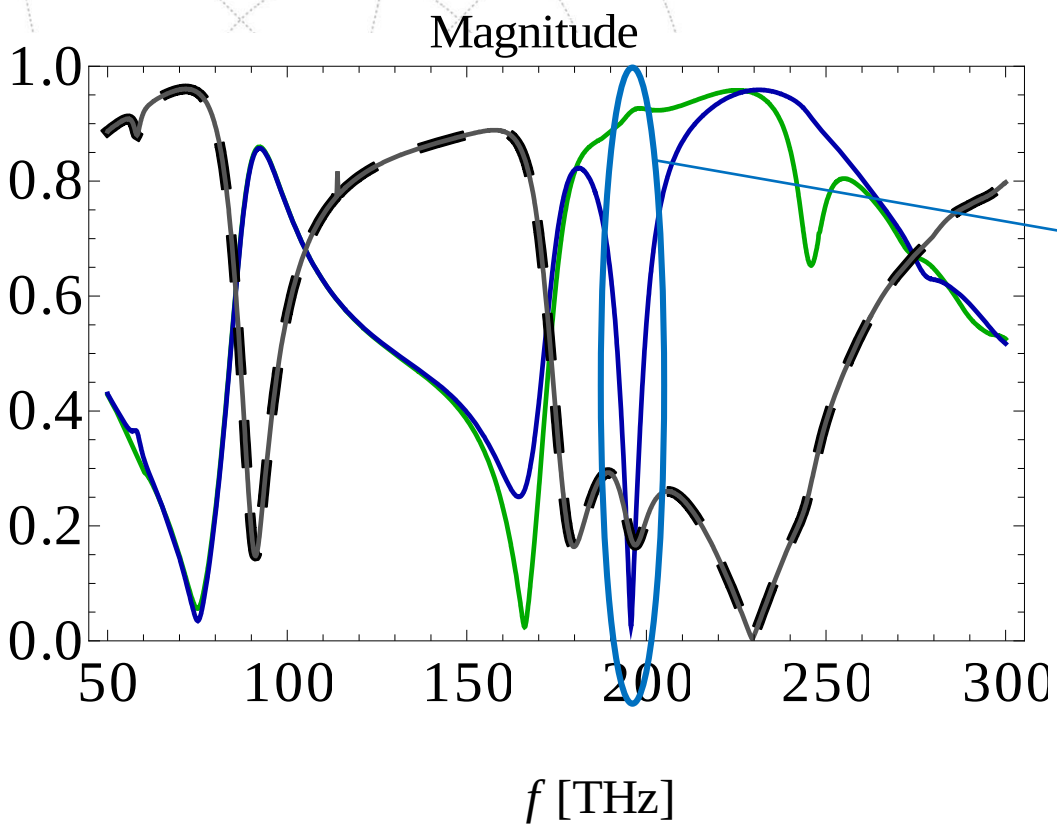
$$T^{\pm} = \mathbf{E}_{\pm}^{\dagger} \cdot \begin{pmatrix} T_{xx} & T_{xy} \\ T_{yx} & T_{yy} \end{pmatrix} \cdot \mathbf{E}_{\pm} \qquad R^{\pm} = \mathbf{E}_{\pm}^{\dagger} \cdot \begin{pmatrix} R_{xx} & R_{xy} \\ R_{yx} & R_{yy} \end{pmatrix} \cdot \mathbf{E}_{\pm} \qquad \mathbf{E}_{\pm} = \left(\hat{\mathbf{x}} \pm i\hat{\mathbf{y}}\right)/\sqrt{2}$$

$$\begin{pmatrix} E_x^t \\ E_y^t \end{pmatrix} = \begin{pmatrix} T_{xx} & T_{xy} \\ T_{yx} & T_{yy} \end{pmatrix} \cdot \begin{pmatrix} E_x^{inc} \\ E_y^{inc} \end{pmatrix} \qquad \begin{pmatrix} E_x^r \\ E_y^r \end{pmatrix} = \begin{pmatrix} R_{xx} & R_{xy} \\ R_{yx} & R_{yy} \end{pmatrix} \cdot \begin{pmatrix} E_x^{inc} \\ E_y^{t_{inc}} \end{pmatrix}$$

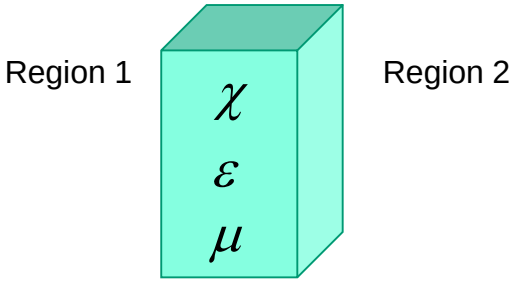
$$T^{\pm} = T_{xx} \pm iT_{xy} \qquad R^{\pm} = R_{xx} \pm iR_{xy}$$

Numerical Examples

Gammadion metamaterial – Transmission Properties



$$\frac{F_{z.av}}{A} = W_{av}^{inc}\left(1+\left|\cancel{R}-\frac{e^{i2k_0l}T_{21}\cancel{T_{12}}}{1+\cancel{R}e^{i2k_0l}}\right|^2-2\left|\frac{\cancel{T_{21}}}{1+\cancel{R}e^{i2k_0l}}\right|^2\right)$$



$$T_{12}^{-} = T_{21}^{+}$$

$$T_{12}^{+} = T_{21}^{-}$$

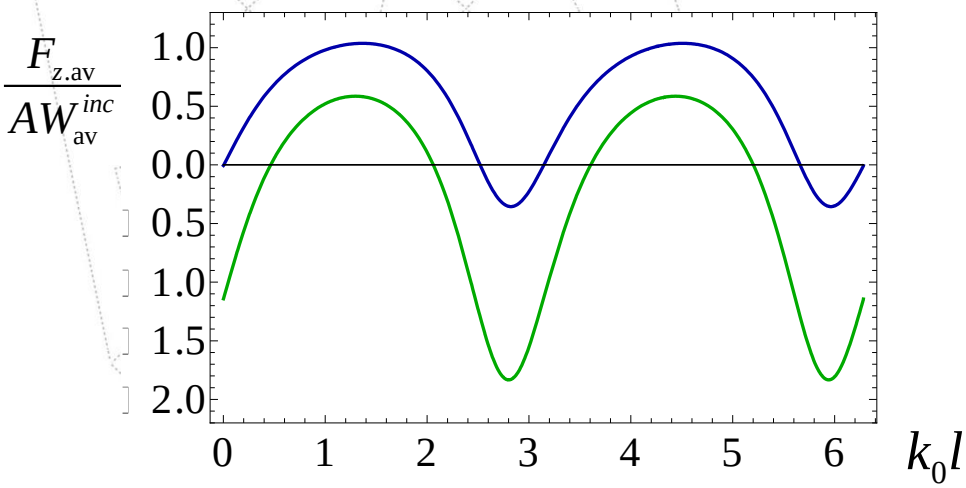
$$R_1^{+} = R_1^{-} = R_2^{+} = R_2^{-}$$

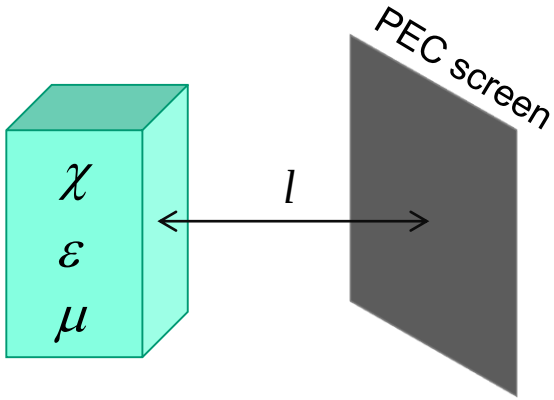
$|T_{12}^{-}|$ $|R_1^{+}|$

$|T_{12}^{+}|$ $|R_1^{-}|$

Example 1

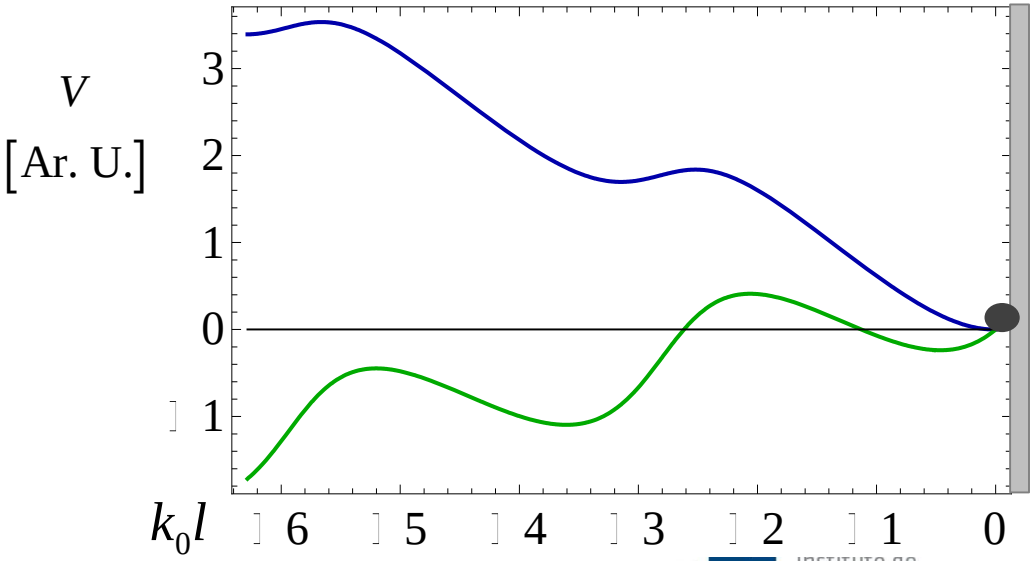
$f_0 = 190\text{THz}$





RCP *LCP*

$k_0 = 2\pi f_0 / c$

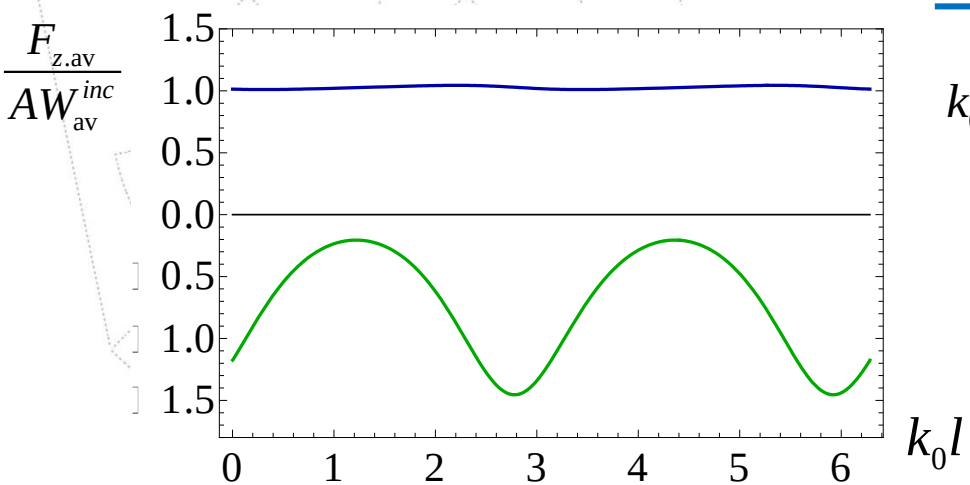


Potential energy

$$V = -\int F_{z,av} dx$$

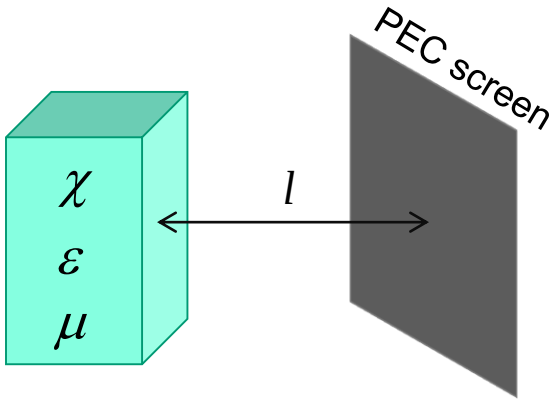
Example 2

$f_0 = 196\text{THz}$

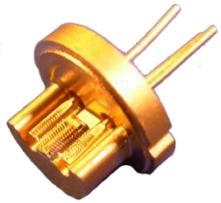


RCP *LCP*

$k_0 = 2\pi f_0 / c$



Seminex Laser Diode T09-118
http://www.seminex.com/

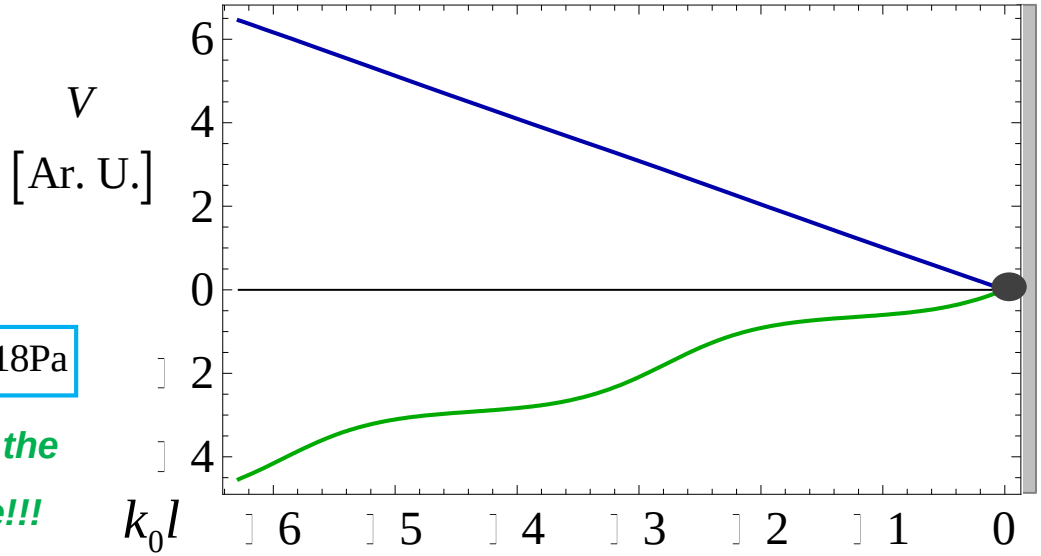


$S^{inc} \approx 21.1\text{GW/m}^2$

$\left|F_{z.av} / AW_{av}^{inc}\right| = 1.0$

$\left|p\right| = \left|F_{z.av} / A\right| = S^{inc} / c \approx 70.18\text{Pa}$

About 3500 larger than the gravitational pressure!!!



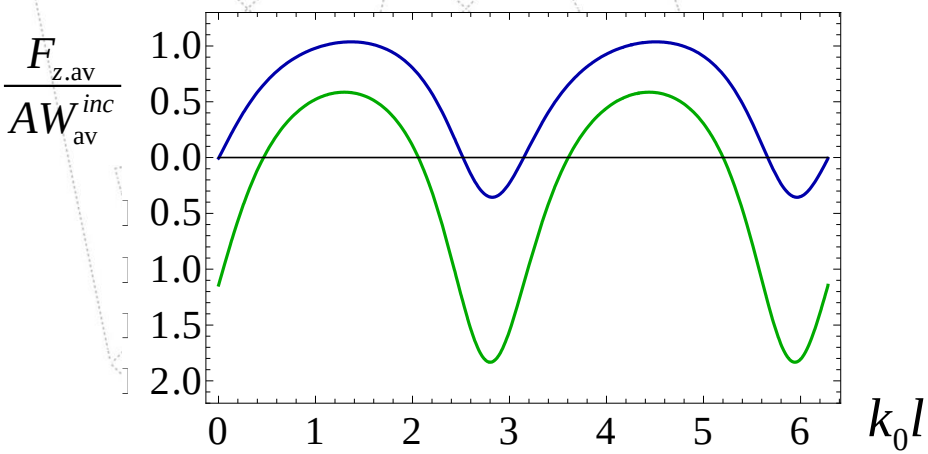
Summary

- Using the proposed tractor beam a chiral body can be optically manipulated at will by controlling the intensity and polarization of the incoming plane wave.
- It is possible to switch from repulsion / attraction simply by switching the polarization of the light.
- The presence of loss, which typically hinders other metamaterial phenomena, is essential to have the proposed effect.
- This idea can be extended to the case of individual chiral particles.

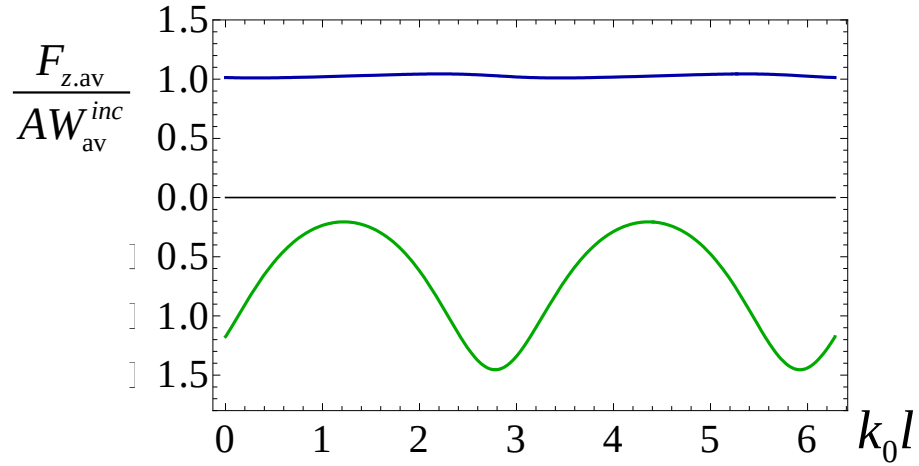
Thank you for your time!

Tractor beam – Attractive Force

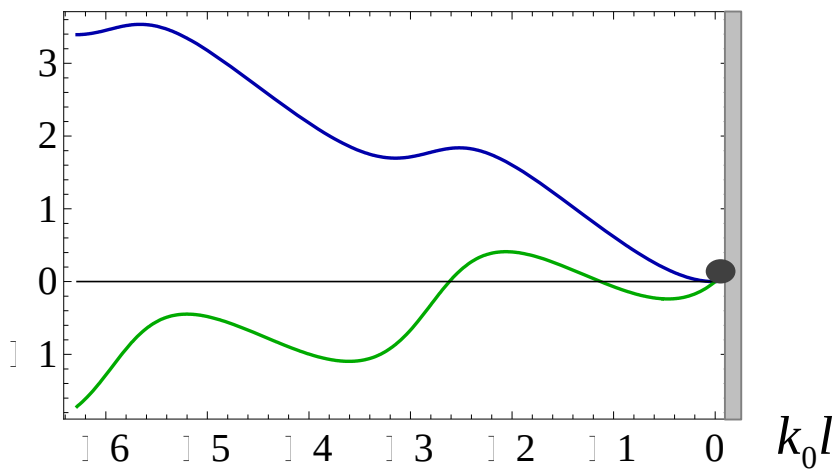
$f_0 = 190\text{THz}$

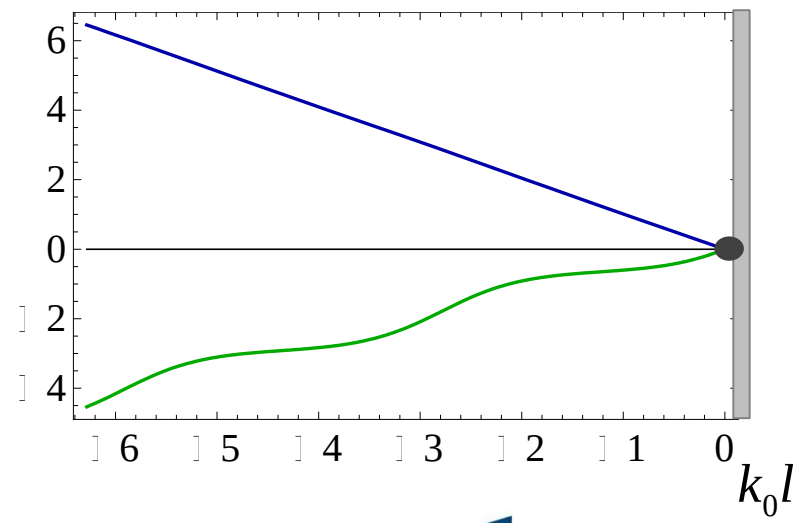


$f_0 = 196\text{THz}$



$$V = -\int F_{z,av} dx$$





RCP *LCP*

$$k_0 = 2\pi f_0 / c$$

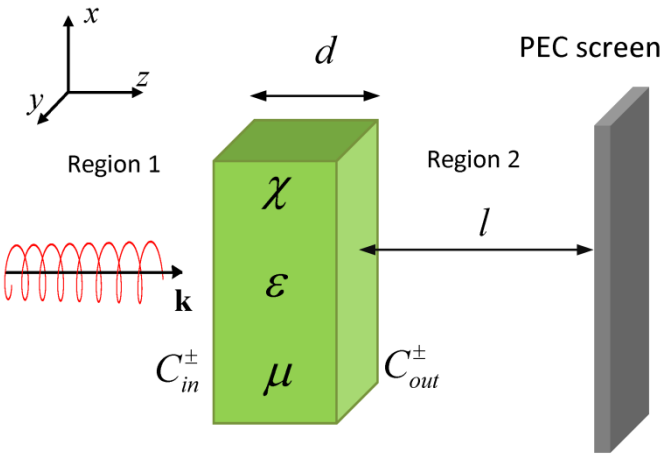
Optical force exerted on the chiral slab

The force acting on the slab of chiral metamaterial:

$$\mathbf{F}_V = \int_{\partial V} dV\, \hat{\mathbf{n}} \cdot \mathrm{Re}\left\{ \underline{\mathbf{T}}_c \right\}$$

Maxwell Stress Tensor:

$$\underline{\mathbf{T}}_c = \frac{1}{2}\left[\varepsilon_0 \mathbf{E} \otimes \mathbf{E}^* - \frac{1}{2}\varepsilon_0 \mathbf{E}\cdot\mathbf{E}^* \underline{\mathbf{1}} + \frac{1}{\mu_0}\mathbf{B}\otimes\mathbf{B}^* - \frac{1}{2\mu_0}\mathbf{B}\cdot\mathbf{B}^* \underline{\mathbf{1}} \right]$$



Field Distribution outside the slab:

$$\mathbf{E}(z) = \left[C^+(z) + C^-(z) \right] \mathbf{e}_\pm \qquad \eta_0 \mathbf{H}(z) = -\left[C^+(z) - C^-(z) \right] (\pm i)\, \mathbf{e}_\pm$$

Average force along the *z*-direction:

$$\frac{F_{z.\mathrm{av}}}{A} = -\frac{\varepsilon_0}{2}\left(\left|C_{out}^+\right|^2 + \left|C_{out}^-\right|^2 - \left|C_{in}^+\right|^2 - \left|C_{in}^-\right|^2 \right)$$

$$\begin{pmatrix} C_{in}^- \\ C_{out}^+ \end{pmatrix} = \begin{pmatrix} R & T_{12} \\ T_{21} & R \end{pmatrix} \begin{pmatrix} C_{in}^+ \\ C_{out}^- \end{pmatrix} \qquad C_{out}^- = -e^{i2k_0 l} C_{out}^+$$