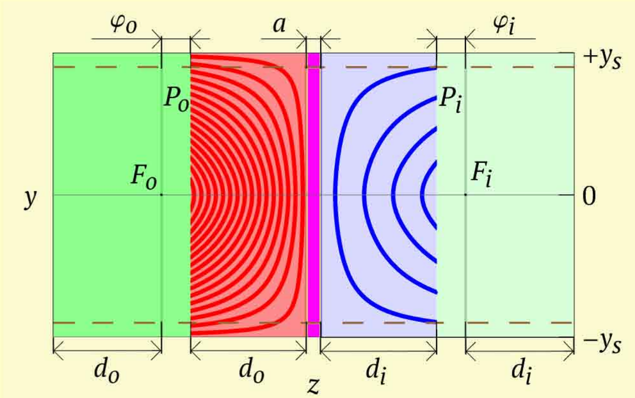
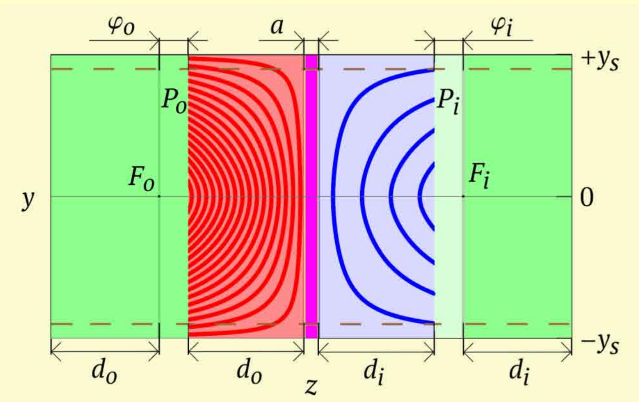
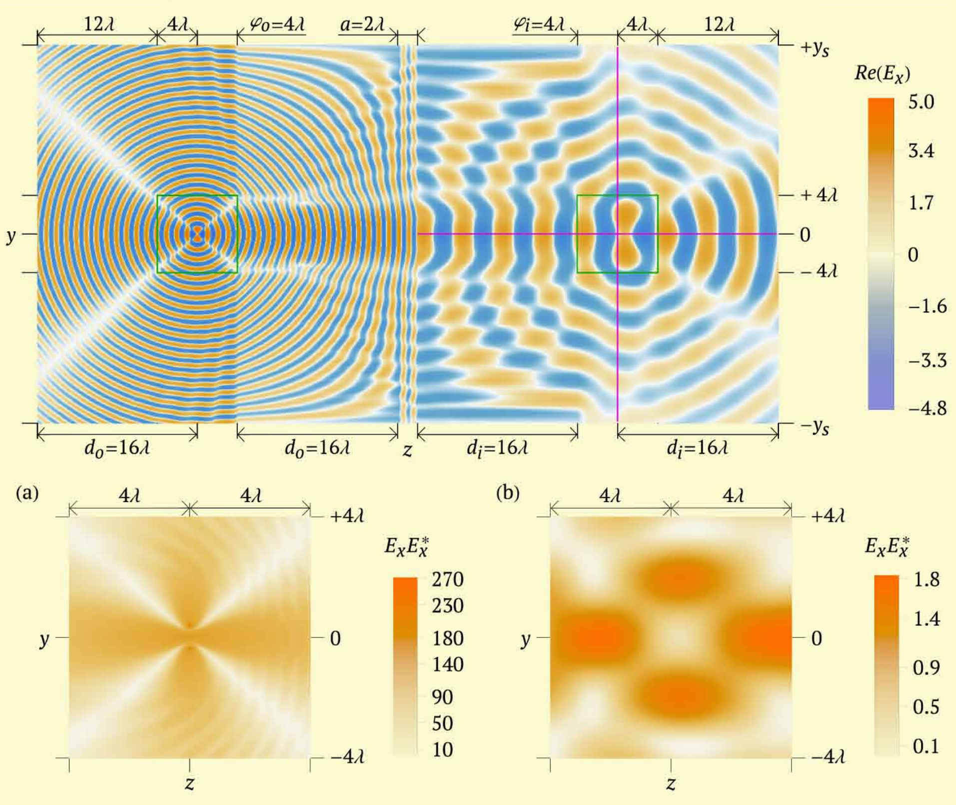
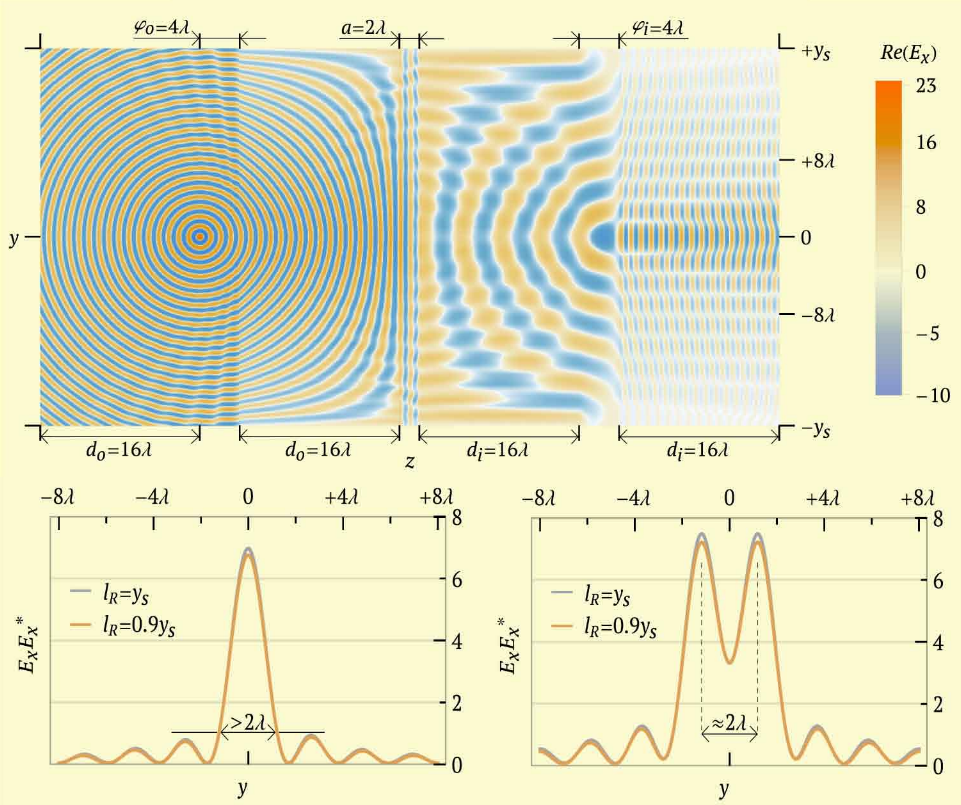
Summary







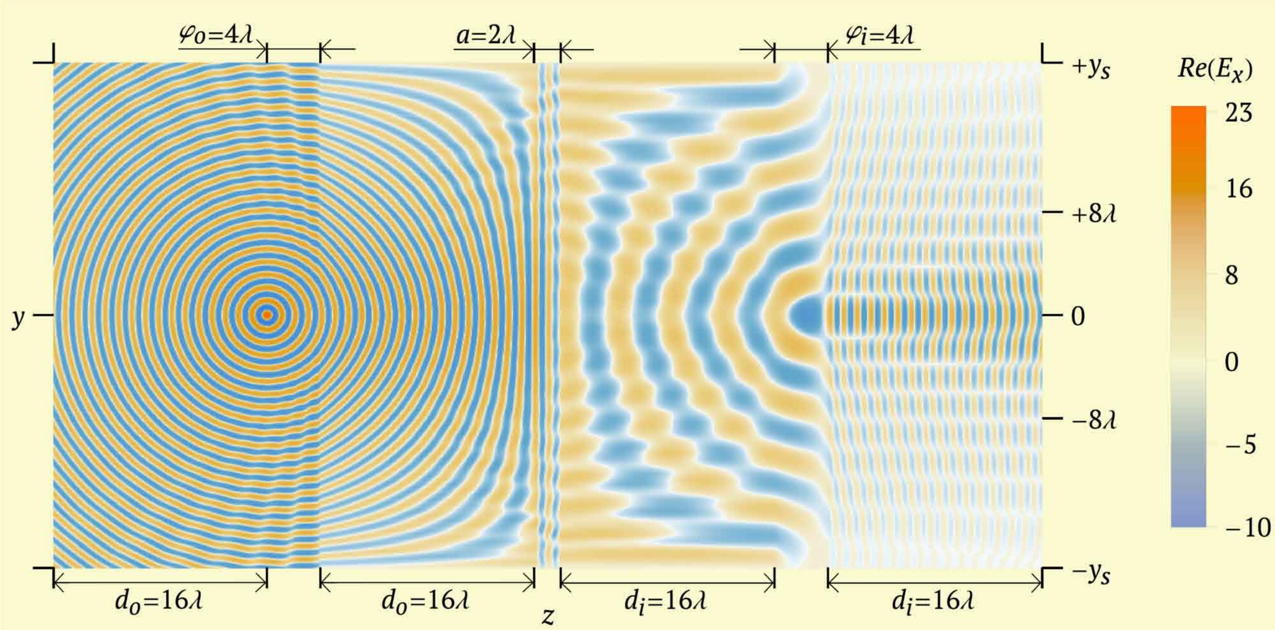


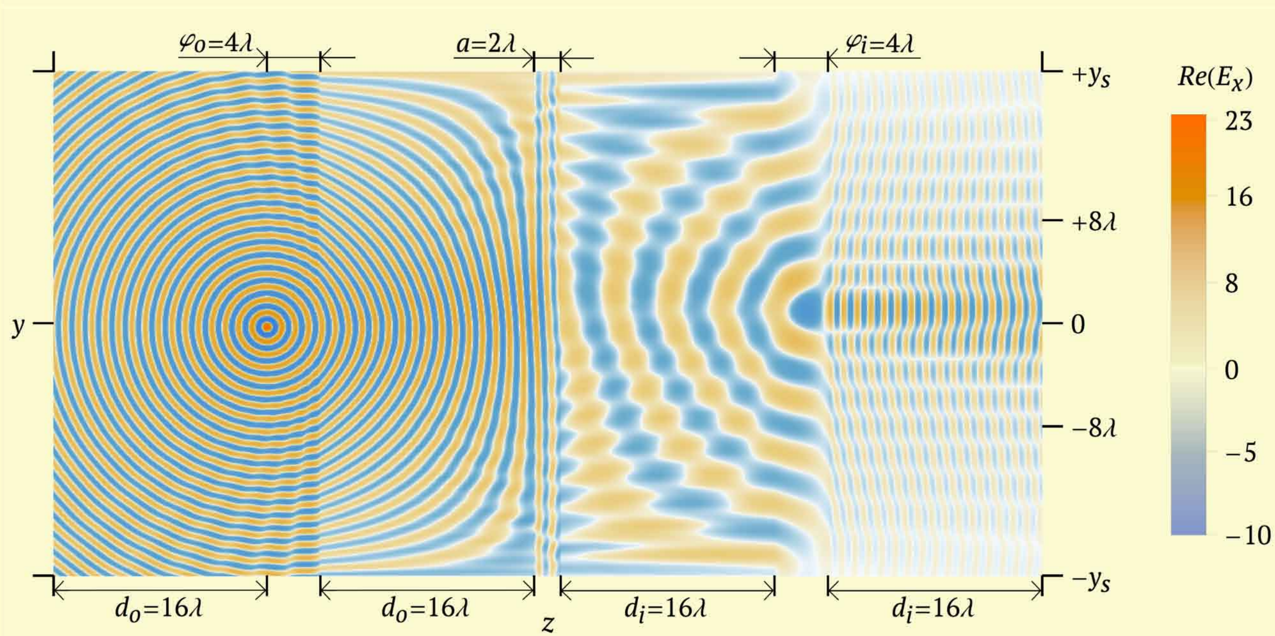
Contact information: Mircea Giloan, e-mail: mircea_giloan@yahoo.com

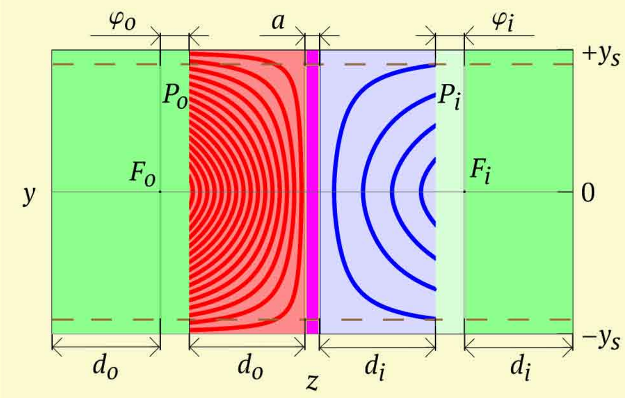
Company for Applied Informatics, Cluj-Napoca, Romania

3) Optical imaging devices based on flat lenses

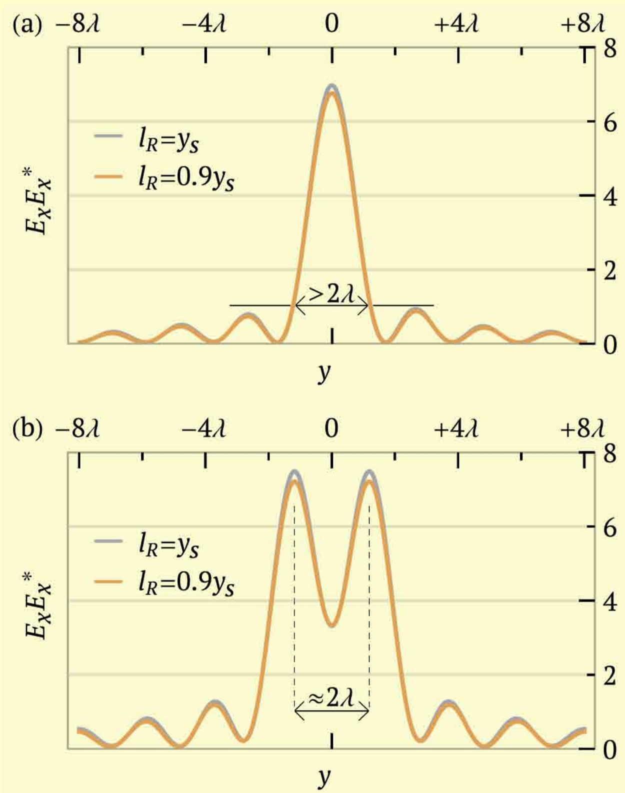
2D FDTD simulations





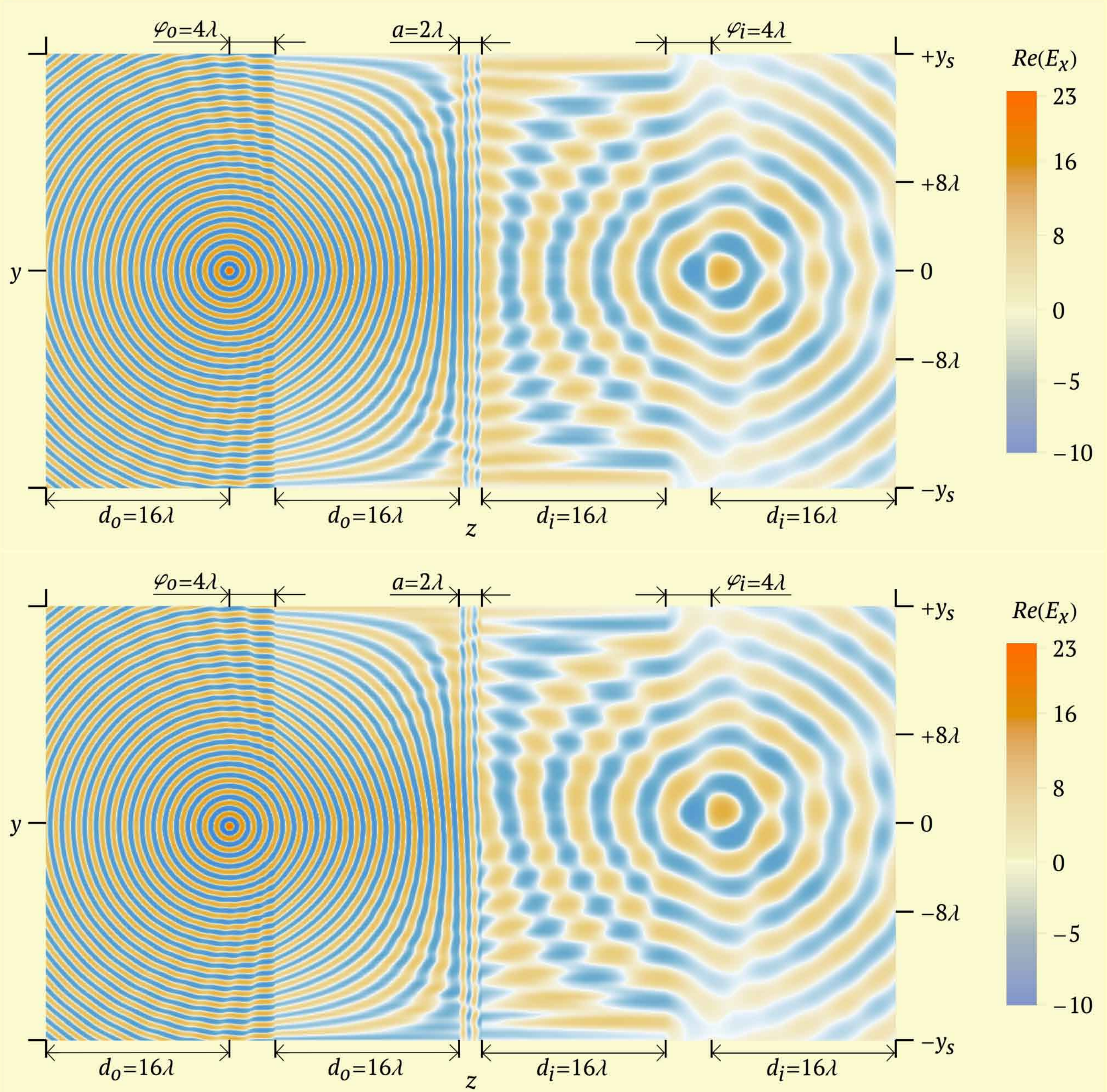


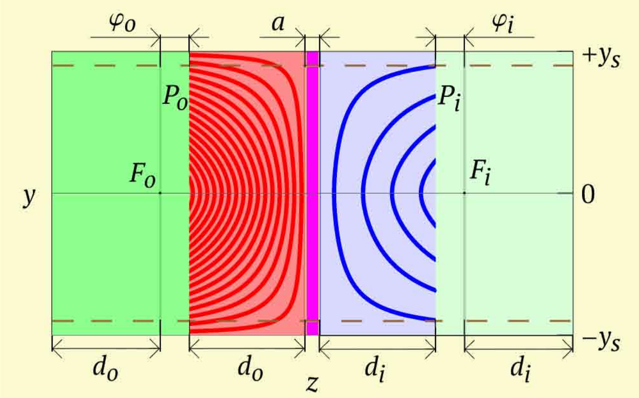
$\sigma_o=\lambda/2$ $4\times$ $\sigma_i\approx 2\lambda$



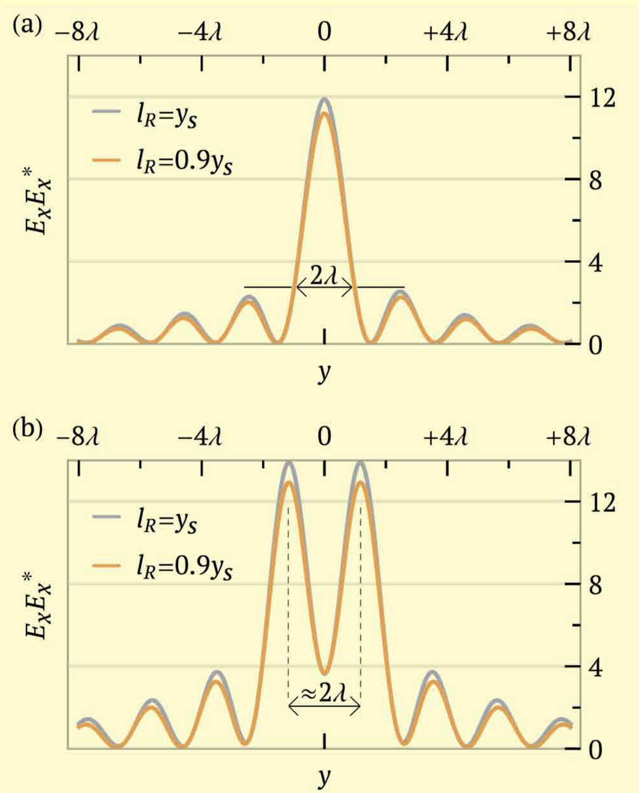
3) Optical imaging devices based on flat lenses

2D FDTD simulations



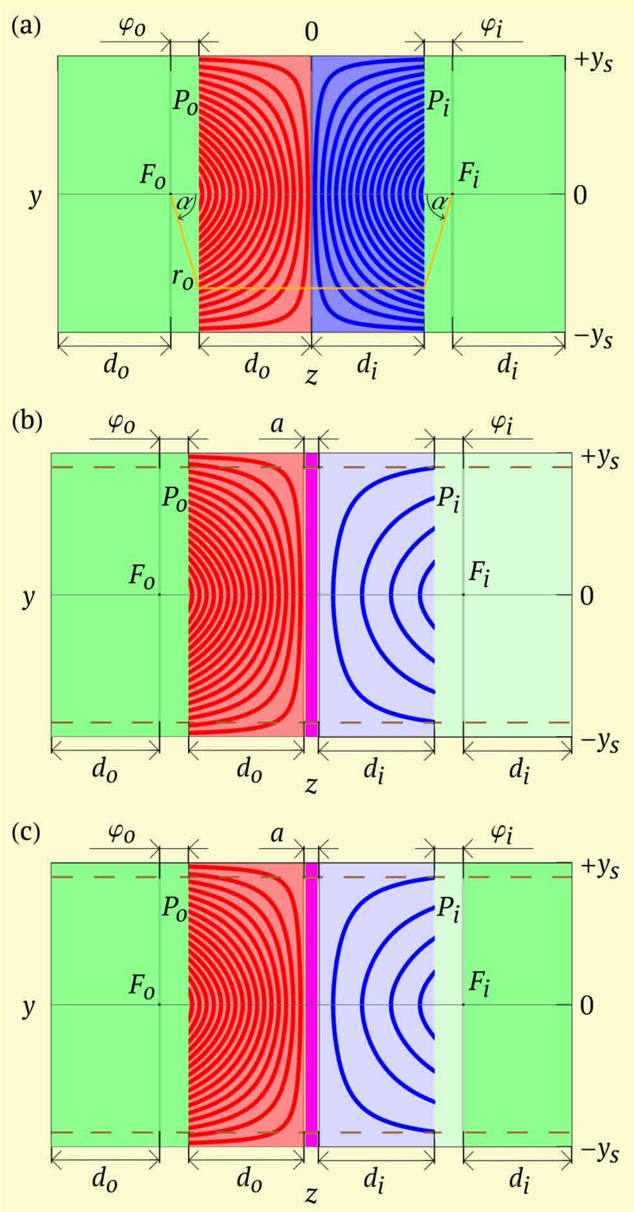


$\sigma_o = \lambda/2$ $4\times$ $\sigma_i \approx 2\lambda$



3) Optical imaging devices based on flat lenses

Optical imaging device

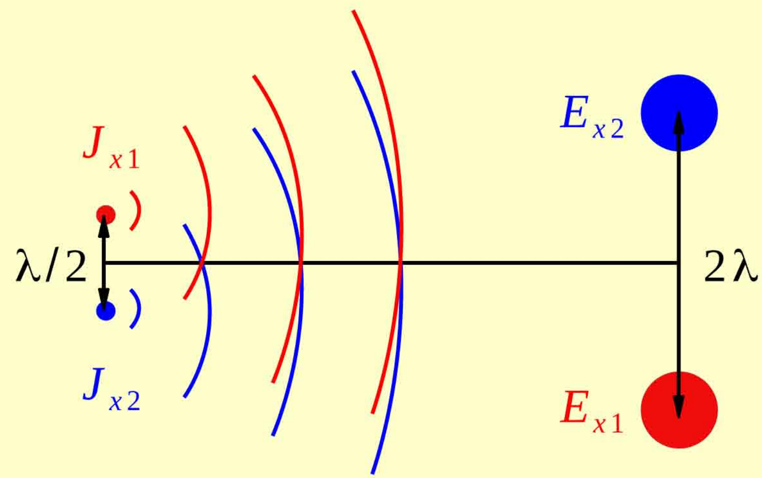


Incoherent dipole sources

$$\{E_x, H_y, H_z\}$$

$$J_x = J_0 e^{-(t-t_0)^2/2\tau^2} e^{-i\omega t + \phi}$$

$$\tau = T/(\sqrt{2}) \qquad \omega = 2\pi/T$$



$$J_{x1} = J_1 e^{-i\omega t} \qquad J_{x2} = J_2 e^{-i\omega t + \phi}$$

$$I_1 = E_{x1} \cdot E_{x1}^* \qquad I_2 = E_{x2} \cdot E_{x2}^*$$

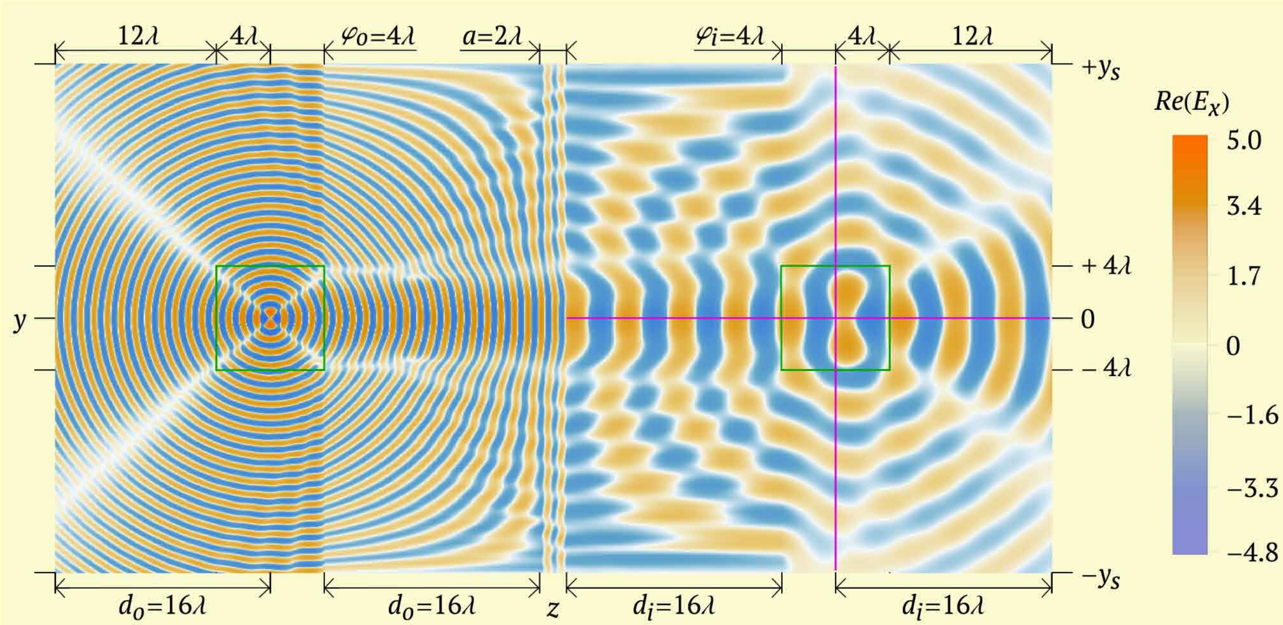
$$I = \frac{1}{2\pi} \int_0^{2\pi} (E_{x1} + E_{x2}) \cdot (E_{x1} + E_{x2})^* \, d\phi = I_1 + I_2$$

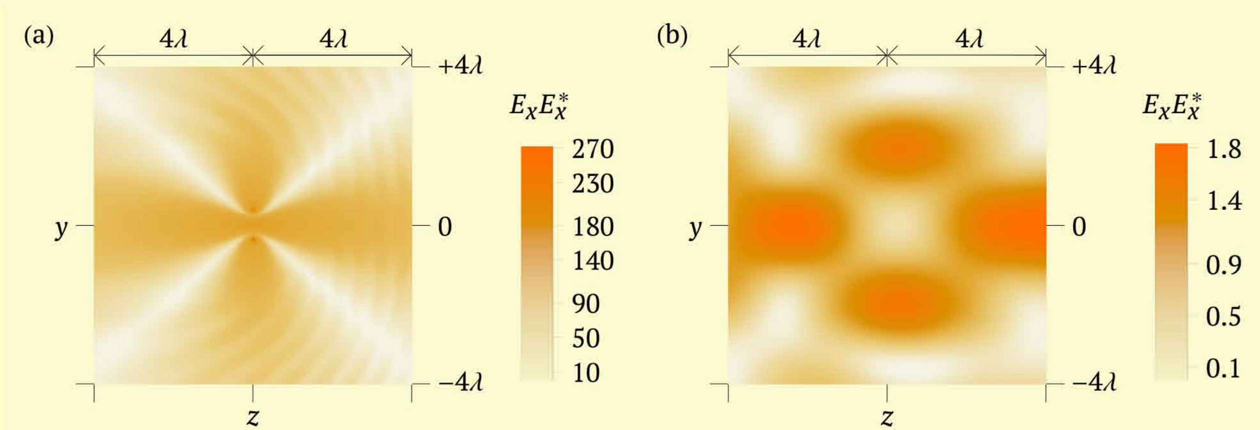
3) Optical imaging devices based on flat lenses

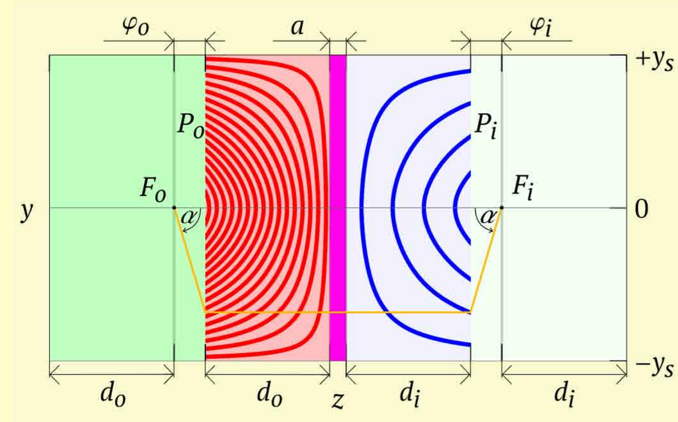
2D FDTD simulations – in phase dipole souces

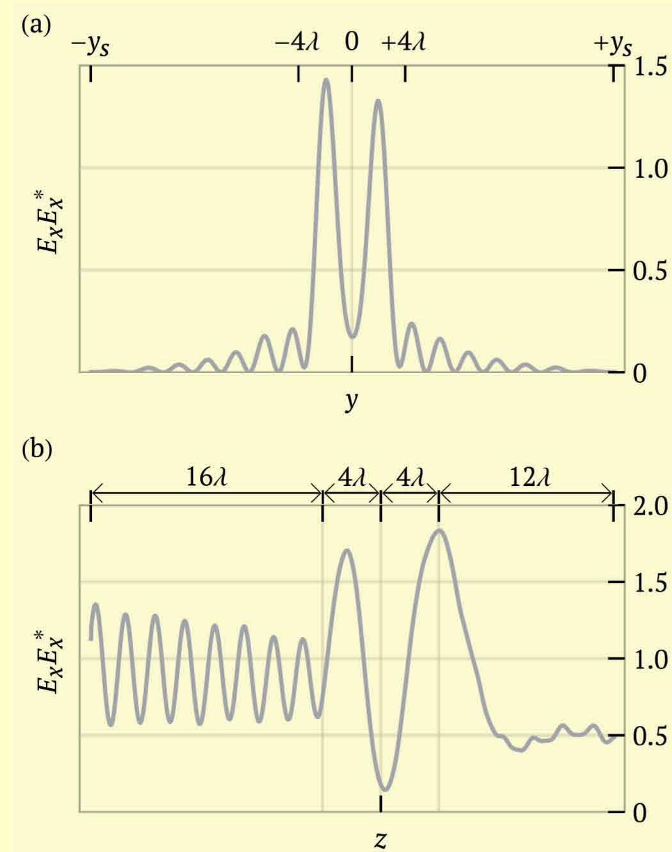
$\{E_x, H_y, H_z\}$ $\Delta = \lambda/40$ $\Delta t = \Delta/(c\sqrt{2})$ $c = 1$

$\sigma_o = 3\lambda/4$ $4\times$ $\sigma_i \approx 3\lambda$



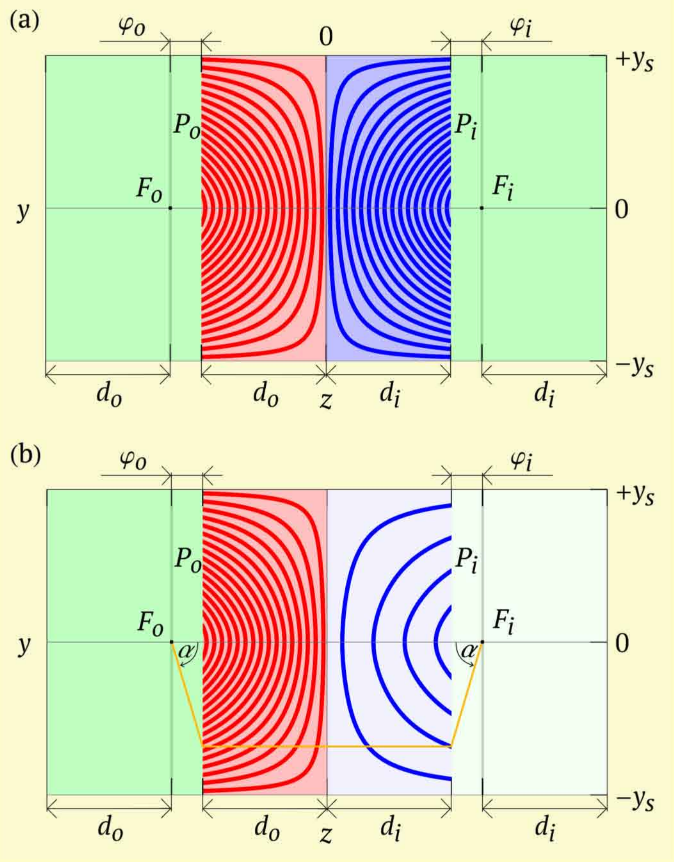






3) Optical imaging devices based on flat lenses

Optical imaging device



$\rho = 4$

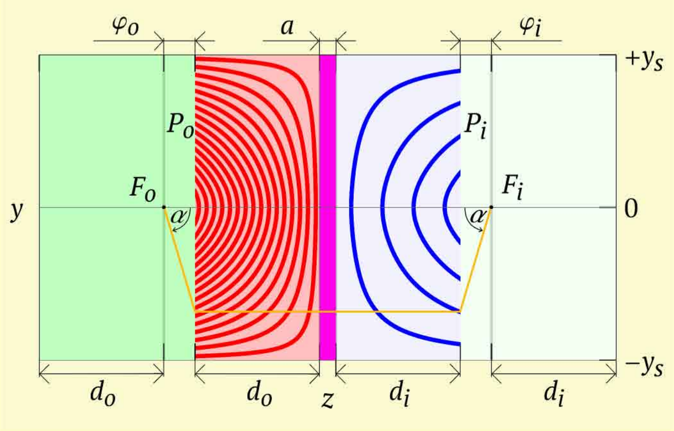
$$h(x,y) = m\left(\delta - \gamma \cdot \left(\varphi^2 + (x - x_F)^2 + (y - y_F)^2\right)^{1/2}\right)$$

$\delta = 1 + \varphi / d$ $\quad \gamma = 1/d$ $\quad \rho = d/\varphi$

$m_o = 1 \quad m_i = 1/4$

$\varepsilon = \mu = 1 \quad \varepsilon = \mu = 1/4$

Absorbing layer



$$t_o = \frac{2\cos(\alpha)}{1 + \cos(\alpha)} \qquad t_i = \frac{2}{1 + \cos(\alpha)}$$

$$y_s = \varphi(\rho(\rho + 2))^{1/2}$$

$$\cos(\alpha_s) = (\rho + 1)^{-1}$$

$$t_{om} = \frac{2}{\rho + 2} \qquad t_{im} = \frac{2(\rho + 1)}{\rho + 2}$$

$$abs = \frac{t_{om} t_{im}}{t_o t_i}$$

Flat lens - numerical simulations

Converging lens - constitutive tensor eigenvalues

$$h(x,y)=\delta-\gamma\cdot\left(\varphi^2+(x-x_F)^2+(y-y_F)^2\right)^{1/2}$$

$$\gamma=+1/z_D$$

$$\varphi>0$$

$$\delta=1+\varphi/z_D$$

$$(x-x_F)^2+(y-y_F)^2=z_D\cdot(z_D+2\varphi)$$

$h(x,y)\leqslant 0$ →

$$\lambda_1\in(-\infty,0]$$
$$\lambda_2\in(-\infty,-1]$$
$$\lambda_3\in[-1,0)$$

$0<h(x,y)\leqslant 1$ →

$$\lambda_1\in(0,1]$$
$$\lambda_2\in(0,1]$$
$$\lambda_3\in[1,\infty)$$

Mapping eigenvalues to a free loss Drude dispersive material model

$$\lambda_i(\omega)=\varepsilon_{i\infty}-\frac{\omega_{ip}^2}{\omega^2-i\omega\gamma_i}\quad\xrightarrow{\gamma_i=0}\quad\lambda_i(\omega)=\frac{\omega^2\varepsilon_{i\infty}-\omega_{ip}^2}{\omega^2}$$

$$\varepsilon_{i\infty}=max(1,\lambda_1)$$

$$\omega_{ip}^2=\omega_0^2(\varepsilon_{i\infty}-\lambda_i)$$

Flat lens - numerical simulations

Finite Differences Time Domain numerical simulations

$$\frac{\partial \boldsymbol{B}}{\partial t} = -\nabla \times \boldsymbol{E} - \boldsymbol{M}$$

$$\boldsymbol{H} = \mu_0^{-1} \mu^{-1} \boldsymbol{B}$$

$$\frac{\partial \boldsymbol{D}}{\partial t} = \nabla \times \boldsymbol{H} - \boldsymbol{J}$$

$$\boldsymbol{E} = \varepsilon_0^{-1} \varepsilon^{-1} \boldsymbol{D}$$

$$\varepsilon = \mu = \begin{pmatrix} h & 0 & -z h_x \\ 0 & h & -z h_y \\ -z h_x & -z h_y & \dfrac{g^2+1}{h} \end{pmatrix}$$

$$g^2 = z^2 (h_x^2 + h_y^2)$$

$$n = \begin{pmatrix} n_{xx} & 0 & n_{xz} \\ 0 & n_{yy} & n_{yz} \\ n_{xz} & n_{yz} & n_{zz} \end{pmatrix}$$

$$n_{xx} = n_{yy} = h$$

$$n_{xz} = -z h_x$$

$$n_{yz} = -z h_y$$

$$n_{zz} = \frac{g^2+1}{h}$$

Normal diagonal decomposition of permittivity and permeability tensors

$$n = D \cdot \Lambda \cdot D^T$$

$$n^{-1} = D \cdot \Lambda^{-1} \cdot D^T$$

$$D \cdot D^T = 1$$

$$\Lambda = \begin{pmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{pmatrix}$$

$$\lambda_1 = h \qquad \lambda_{2,3} = \frac{1}{2}\left(n_{yy} + n_{zz} \mp \sqrt{(n_{yy} + n_{zz})^2 - 4}\right)$$

$$D = \begin{pmatrix} -\rho_y & \rho_x \xi & \rho_x \beta \xi \\ \rho_x & \rho_y \xi & \rho_y \beta \xi \\ 0 & \beta \xi & -\xi \end{pmatrix}$$

$$\beta = \frac{\lambda_2 - n_{yy}}{\sqrt{n_{xz}^2 + n_{yz}^2}}$$

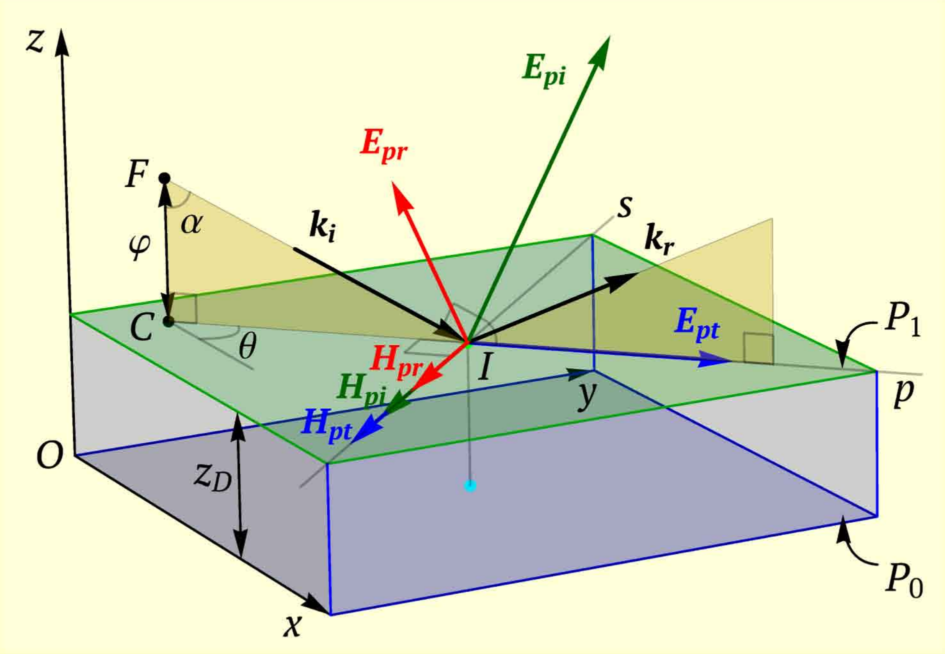
$$\xi = (1 + \beta^2)^{-1/2}$$

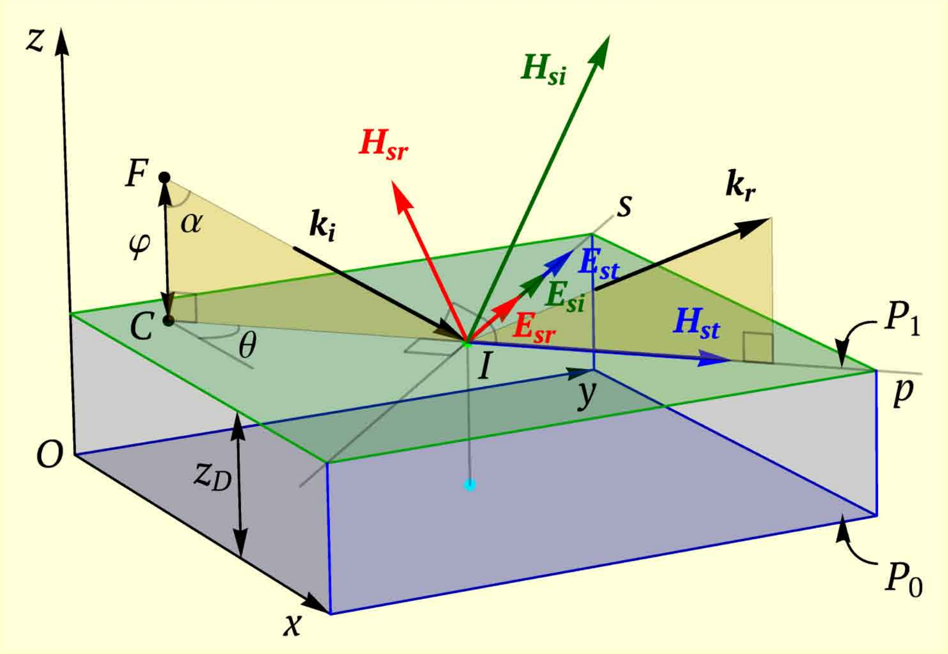
$$\rho_x = \frac{n_{xz}}{\sqrt{n_{xz}^2 + n_{yz}^2}} \qquad \rho_x = \frac{n_{yz}}{\sqrt{n_{xz}^2 + n_{yz}^2}}$$

N. Okada and J. B. Cole, FDTD modeling of a cloak with a nondiagonal permittivity tensor, ISRN Opt. 2012, 536209 (2012).

2) Reflection and transmission of flat lenses media

Reflection and transmission coefficients – backward propagation





$$E_{pi}=H_{pi}$$
$$E_{pr}=H_{pr}$$
$$E_{pt}=H_{pt}$$

$$E_{pi}\cos\alpha - E_{pr}\cos\alpha = E_{pt}$$
$$H_{pi}+H_{pr}=H_{pt}$$

$$E_{si}=H_{si}$$
$$E_{sr}=H_{sr}$$
$$E_{st}=H_{st}$$

$$E_{si}+E_{sr}=E_{st}$$
$$H_{si}\cos\alpha - H_{sr}\cos\alpha = H_{st}$$

$$r=\frac{E_{pr}}{E_{pi}}=\frac{E_{sr}}{E_{si}}=-\frac{1-\cos\alpha}{1+\cos\alpha}$$

$$t=\frac{E_{pt}}{E_{pi}}=\frac{E_{st}}{E_{si}}=\frac{2\cos\alpha}{1+\cos\alpha}$$

$$R=r^2$$

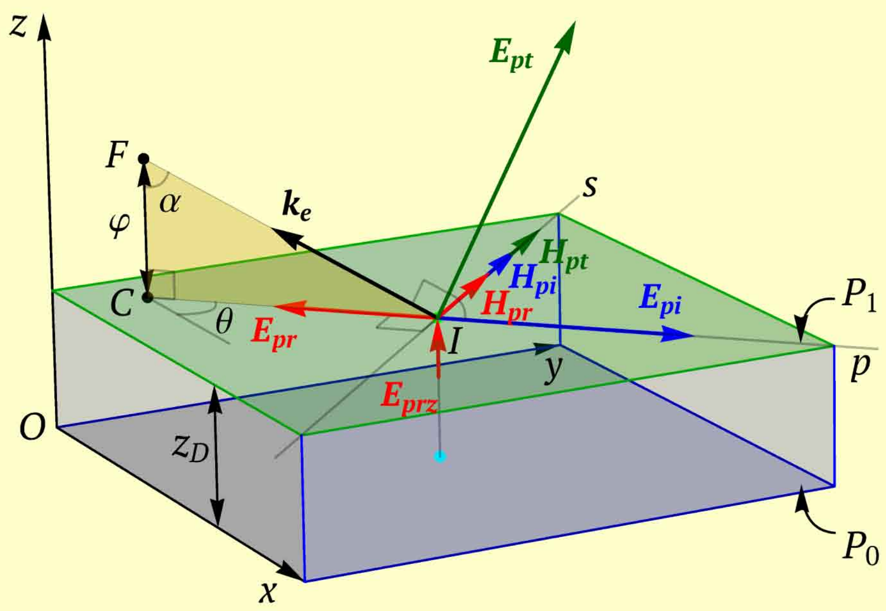
$$T=t^2/\cos\alpha$$

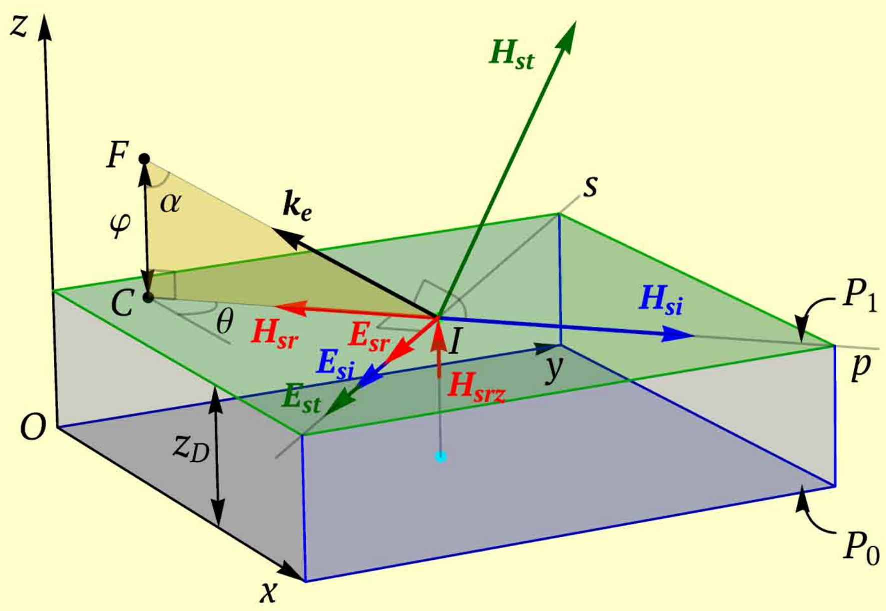
$$R+T=1$$

M. Giloan, Designing Devices for Wave-Vector Manipulation Using a Transformation-Optics Approach, Phys. Rev. Applied 8, 014005 (2017)

2) Reflection and transmission of flat lenses media

Reflection and transmission coefficients – forward propagation





$$E_{pi} = H_{pi}$$
$$E_{pr} = H_{pr}$$
$$E_{pt} = H_{pt}$$

$$E_{pi} - E_{pr} = E_{pt} \cos\alpha$$
$$H_{pi} + H_{pr} = H_{pt}$$

$$E_{si} = H_{si}$$
$$E_{sr} = H_{sr}$$
$$E_{st} = H_{st}$$

$$E_{si} + E_{sr} = E_{st}$$
$$H_{si} - H_{sr} = H_{st} \cos\alpha$$

$$r = \frac{E_{pr}}{E_{pi}} = \frac{E_{sr}}{E_{si}} = \frac{1 - \cos\alpha}{1 + \cos\alpha}$$

$$t = \frac{E_{pt}}{E_{pi}} = \frac{E_{st}}{E_{si}} = \frac{2}{1 + \cos\alpha}$$

$$R = r^2$$

$$T = t^2 \cos\alpha$$

$$R + T = 1$$

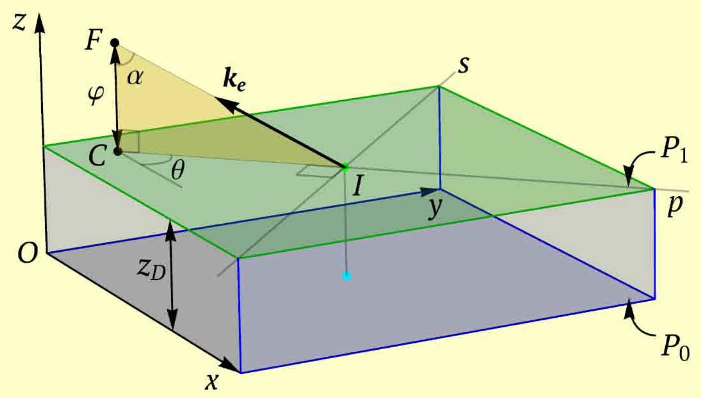
M. Giloan, Designing Devices for Wave-Vector Manipulation Using a Transformation-Optics Approach, Phys. Rev. Applied 8, 014005 (2017)

2) Reflection and transmission of flat lenses media

Incident wave at the output interface of the lens – forward propagation

$$M_i = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1/h \end{pmatrix} \xrightarrow{M_i \cdot \boldsymbol{E}_i = 0} \boldsymbol{E}_i \begin{pmatrix} E_{xi} \\ E_{yi} \\ 0 \end{pmatrix}$$

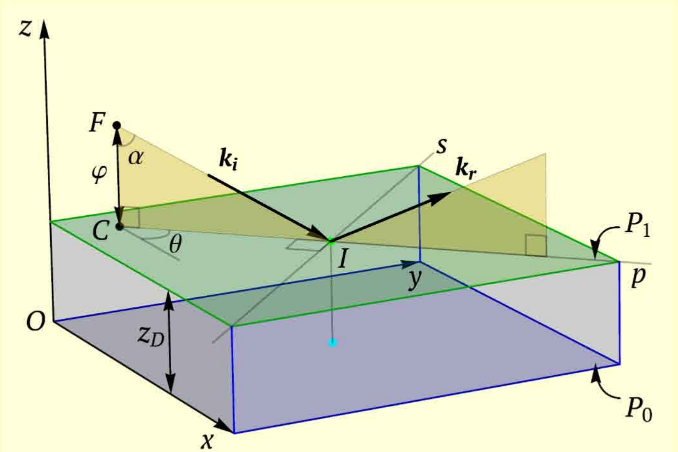
$$P_i = \begin{pmatrix} 0 & -1 & z_D \cdot h_y/h \\ 1 & 0 & -z_D \cdot h_x/h \\ 0 & 0 & 0 \end{pmatrix} \xrightarrow{P_i \cdot \boldsymbol{E}_i = \boldsymbol{H}_i} \boldsymbol{H}_i \begin{pmatrix} H_{xi} \\ H_{yi} \\ 0 \end{pmatrix}$$



Transmitted wave at the output interface of the lens – backward propagation

$$M_t = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1/h \end{pmatrix} \xrightarrow{M_t \cdot \boldsymbol{E}_t = 0} \boldsymbol{E}_t \begin{pmatrix} E_{xt} \\ E_{yt} \\ 0 \end{pmatrix}$$

$$P_t = \begin{pmatrix} 0 & 1 & -z_D \cdot h_y/h \\ -1 & 0 & z_D \cdot h_x/h \\ 0 & 0 & 0 \end{pmatrix} \xrightarrow{P_t \cdot \boldsymbol{E}_t = \boldsymbol{H}_t} \boldsymbol{H}_t \begin{pmatrix} H_{xt} \\ H_{yt} \\ 0 \end{pmatrix}$$



Y. A. Kravtsov and Y. I. Orlov, Geometrical Optics of Inhomogeneous Media (Springer-Verlag, Berlin, 1990).

2) Reflection and transmission of flat lenses media

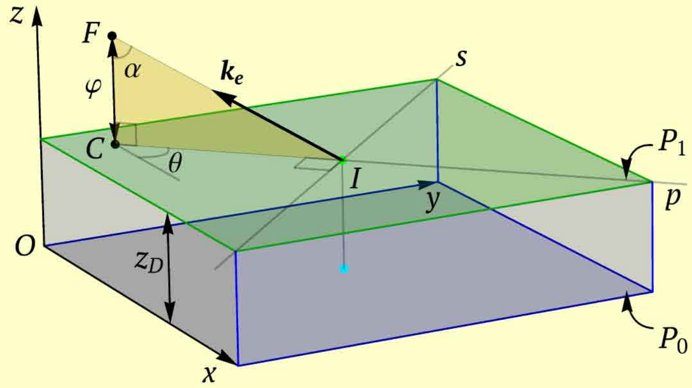
Reflected wave at the output interface of the lens – forward propagation

$$M_r=\begin{pmatrix} \frac{4z_D^2hh_x^2}{(g_D^2+1)^2} & \frac{4z_D^2hh_xh_y}{(g_D^2+1)^2} & \frac{-2z_Dh_x}{g_D^2+1} \\ \frac{4z_D^2hh_xh_y}{(g_D^2+1)^2} & \frac{4z_D^2hh_y^2}{(g_D^2+1)^2} & \frac{-2z_Dh_y}{g_D^2+1} \\ \frac{-2z_Dh_x}{g_D^2+1} & \frac{-2z_Dh_y}{g_D^2+1} & \frac{1}{h} \end{pmatrix} \xrightarrow{M_r\cdot \boldsymbol{E_r}=0}$$

$$\boldsymbol{E_{pr}}=\begin{pmatrix} -E_{pr}\cos\theta \\ -E_{pr}\sin\theta \\ E_{pr}h\frac{2g_D}{g_D^2+1} \end{pmatrix} \qquad \boldsymbol{E_{sr}}=\begin{pmatrix} E_{sr}\sin\theta \\ -E_{sr}\cos\theta \\ 0 \end{pmatrix}$$

$$P_r=\begin{pmatrix} \frac{-2z_D^2h_xh_y}{g_D^2+1} & \frac{z_D^2(h_x^2-h_y^2)+1}{g_D^2+1} & \frac{z_Dh_y}{h} \\ \frac{z_D^2(h_x^2-h_y^2)-1}{g_D^2+1} & \frac{2z_D^2h_xh_y}{g_D^2+1} & \frac{-z_Dh_x}{h} \\ \frac{-2z_Dhh_y}{g_D^2+1} & \frac{2z_Dhh_x}{g_D^2+1} & 0 \end{pmatrix} \xrightarrow{P_r\cdot \boldsymbol{E_r}=\boldsymbol{H_r}}$$

$$\boldsymbol{H_{pr}}=\begin{pmatrix} -H_{pr}\sin\theta \\ H_{pr}\cos\theta \\ 0 \end{pmatrix} \qquad \boldsymbol{H_{sr}}=\begin{pmatrix} -H_{sr}\cos\theta \\ -H_{sr}\sin\theta \\ H_{sr}h\frac{2g_D}{g_D^2+1} \end{pmatrix}$$



$$h(x,y)=\delta-\gamma\cdot\left(\varphi^2+(x-x_F)^2+(y-y_F)^2\right)^{1/2}$$

$$h_x\cos\theta+h_y\sin\theta=-\gamma g_D$$

$$h_x\sin\theta=h_y\cos\theta$$

$$\sin\alpha=g_D$$

2) Reflection and transmission of flat lenses media

Electromagnetic waves polarization

$$\boldsymbol{E}=\boldsymbol{E}_{\boldsymbol{0}}\mathrm{e}^{i(k_0\boldsymbol{k}\cdot\boldsymbol{r}-\omega t)}$$

$$\boldsymbol{H}=\frac{1}{\eta_0}\boldsymbol{H}_{\boldsymbol{0}}\mathrm{e}^{i(k_0\boldsymbol{k}\cdot\boldsymbol{r}-\omega t)}$$

$$k_0=\omega/c=\omega\sqrt{\varepsilon_0\mu_0}$$

$$\eta_0=\sqrt{\frac{\mu_0}{\varepsilon_0}}$$

→

$$\nabla\times\boldsymbol{E}=-\frac{\partial\boldsymbol{B}}{\partial t}$$

$$\boldsymbol{B}=\mu_0\mu\boldsymbol{H}$$

$$\nabla\times\boldsymbol{H}=\frac{\partial\boldsymbol{D}}{\partial t}$$

$$\boldsymbol{D}=\varepsilon_0\varepsilon\boldsymbol{E}$$

→

$$\boldsymbol{k}\times\boldsymbol{E}_{\boldsymbol{0}}-\mu\boldsymbol{H}_{\boldsymbol{0}}=0$$

$$\boldsymbol{k}\times[\varepsilon^{-1}(\boldsymbol{k}\times\boldsymbol{H}_{\boldsymbol{0}})]+\mu\boldsymbol{H}_{\boldsymbol{0}}=0$$

$$\boldsymbol{k}\times\boldsymbol{H}_{\boldsymbol{0}}+\varepsilon\boldsymbol{E}_{\boldsymbol{0}}=0$$

$$\boldsymbol{k}\times[\mu^{-1}(\boldsymbol{k}\times\boldsymbol{E}_{\boldsymbol{0}})]+\varepsilon\boldsymbol{E}_{\boldsymbol{0}}=0$$

Transformation media

$$\boldsymbol{k}^T=(k_x,k_y,k_z)$$

$$\longmapsto\quad \boldsymbol{k}\times\boldsymbol{F}=K\cdot\boldsymbol{F}$$

$$K=\begin{pmatrix}0 & -k_z & k_y\\ k_z & 0 & -k_x\\ -k_y & k_x & 0\end{pmatrix}$$

$$\longmapsto$$

$$\varepsilon=\mu=n$$

$$P=n^{-1}\cdot K$$

$$M=K\cdot n^{-1}\cdot K+n$$

$$P\cdot\boldsymbol{E}_{\boldsymbol{0}}=\boldsymbol{H}_{\boldsymbol{0}}$$

$$M\cdot\boldsymbol{H}_{\boldsymbol{0}}=0$$

$$P\cdot\boldsymbol{H}_{\boldsymbol{0}}=-\boldsymbol{E}_{\boldsymbol{0}}$$

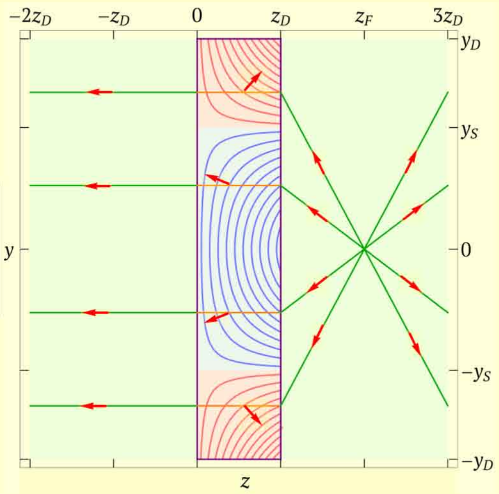
$$M\cdot\boldsymbol{E}_{\boldsymbol{0}}=0$$

M. Rahm, S. A. Cummer, D. Schurig, J. B. Pendry, and D.R. Smith, Optical Design of Reflectionless Complex Media by Finite Embedded Coordinate Transformations, Phys. Rev. Lett. 100, 063903 (2008).

2) Reflection and transmission of flat lenses media

Wave vectors of the incident and reflected waves at the output interface of the lens

backward propagation



from focal point

$$z=z_D,\ k_x=-z_D h_x,\ k_y=-z_D h_y$$

$$H(x,y,k_z)=(k_z+h)(k_z(g_D^2+1)+h(g_D^2-1))/h$$

$$H(x,y,k_z)=0$$

$$k_{zi}=-h$$

$$P_1: z=z_D$$

$$\boldsymbol{k}_t\begin{pmatrix} k_{xt}=-z_D h_x \\ k_{yt}=-z_D h_y \\ k_{zt}=-h \end{pmatrix}$$

$$\boldsymbol{k}_i\begin{pmatrix} k_{xi}=-z_D h_x \\ k_{yi}=-z_D h_y \\ k_{zi} \end{pmatrix}$$

$$k_{xi}^2+k_{yi}^2+k_{zi}^2=1$$

$$\boldsymbol{k}_r\begin{pmatrix} k_{xr}=-z_D h_x \\ k_{yr}=-z_D h_y \\ k_{zr} \end{pmatrix}$$

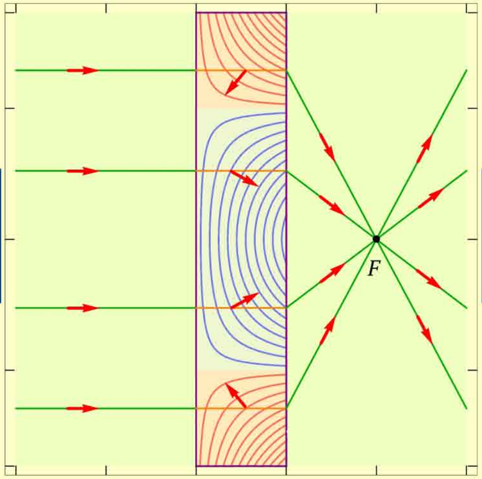
$$k_{xr}^2+k_{yr}^2+k_{zr}^2=1$$

Y. A. Kravtsov and Y. I. Orlov, Geometrical Optics of Inhomogeneous Media (Springer-Verlag, Berlin, 1990).

2) Reflection and transmission of flat lenses media

Wave vectors of the incident and reflected waves at the output interface of the lens

forward propagation



toward focal point

$$z=z_D,\ k_x=z_D h_x,\ k_y=z_D h_y$$

↓

$$H(x,y,k_z)=(k_z-h)(k_z(g_D^2+1)-h(g_D^2-1))/h$$

↓

$$H(x,y,k_z)=0$$

↓

$$k_{zi}=h \qquad k_{zr}=h(g_D^2-1)/(g_D^2+1)$$

$$g_D^2=z_D^2(h_x^2+h_y^2)$$

$$P_1: z=z_D$$

→

$$\boldsymbol{k_i}\begin{pmatrix} k_{xi}=z_D h_x \\ k_{yi}=z_D h_y \\ k_{zi}=h \end{pmatrix}$$

←

$$\boldsymbol{k_r}\begin{pmatrix} k_{xr}=z_D h_x \\ k_{yr}=z_D h_y \\ k_{zr}=h\dfrac{g_D^2-1}{g_D^2+1} \end{pmatrix}$$

$$\boldsymbol{k_t}\begin{pmatrix} k_{xt}=z_D h_x \\ k_{yt}=z_D h_y \\ k_{zt} \end{pmatrix}$$

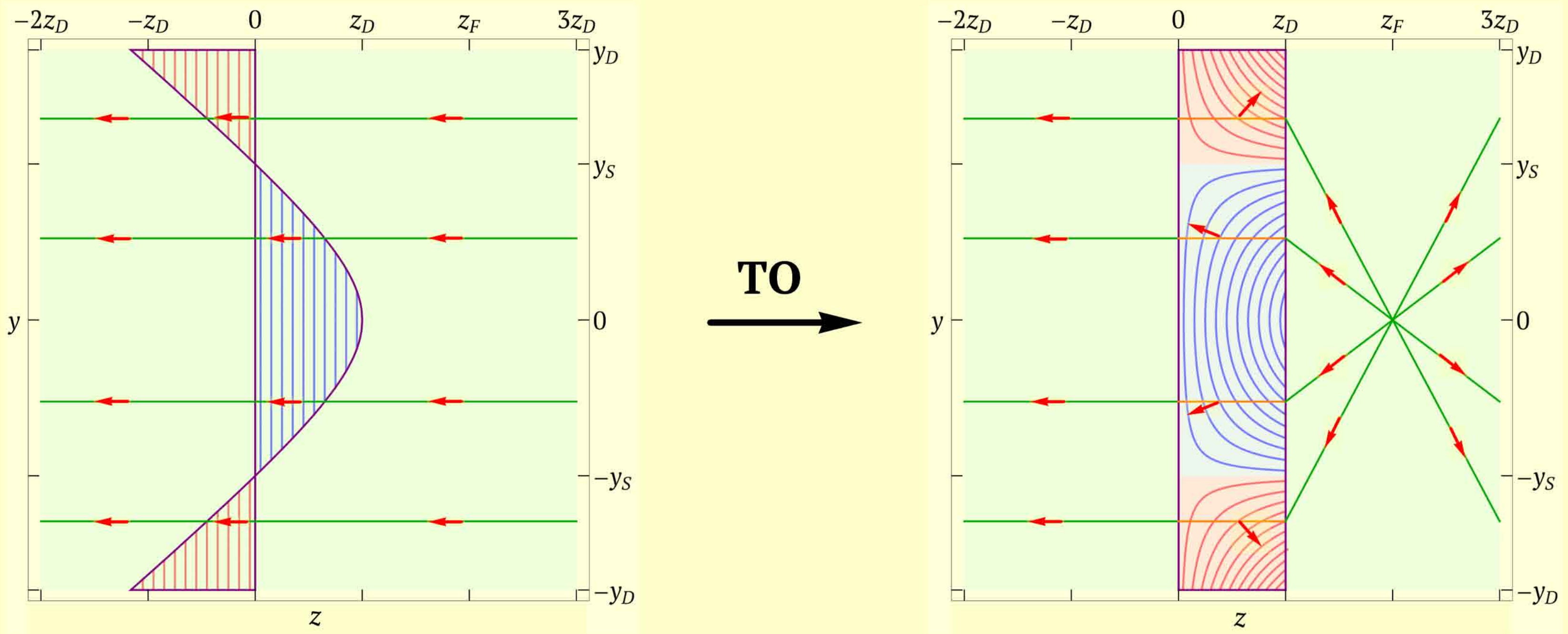
$$k_{xt}^2+k_{yt}^2+k_{zt}^2=1$$

→

Y. A. Kravtsov and Y. I. Orlov, Geometrical Optics of Inhomogeneous Media (Springer-Verlag, Berlin, 1990).

1) Flat lenses designed by transformation-optics

Converging lens – backward propagation (from focal point)



$$h(x,y)=\delta-\gamma\cdot\left(\varphi^2+(x-x_F)^2+(y-y_F)^2\right)^{1/2}$$

$$\gamma=+1/z_D \qquad \varphi=z_D \qquad \delta=2$$

$$(x_S-x_F)^2+(y_S-y_F)^2=z_D\cdot(z_D+2\varphi)$$

$$z\rightarrow z/h(x,y)$$

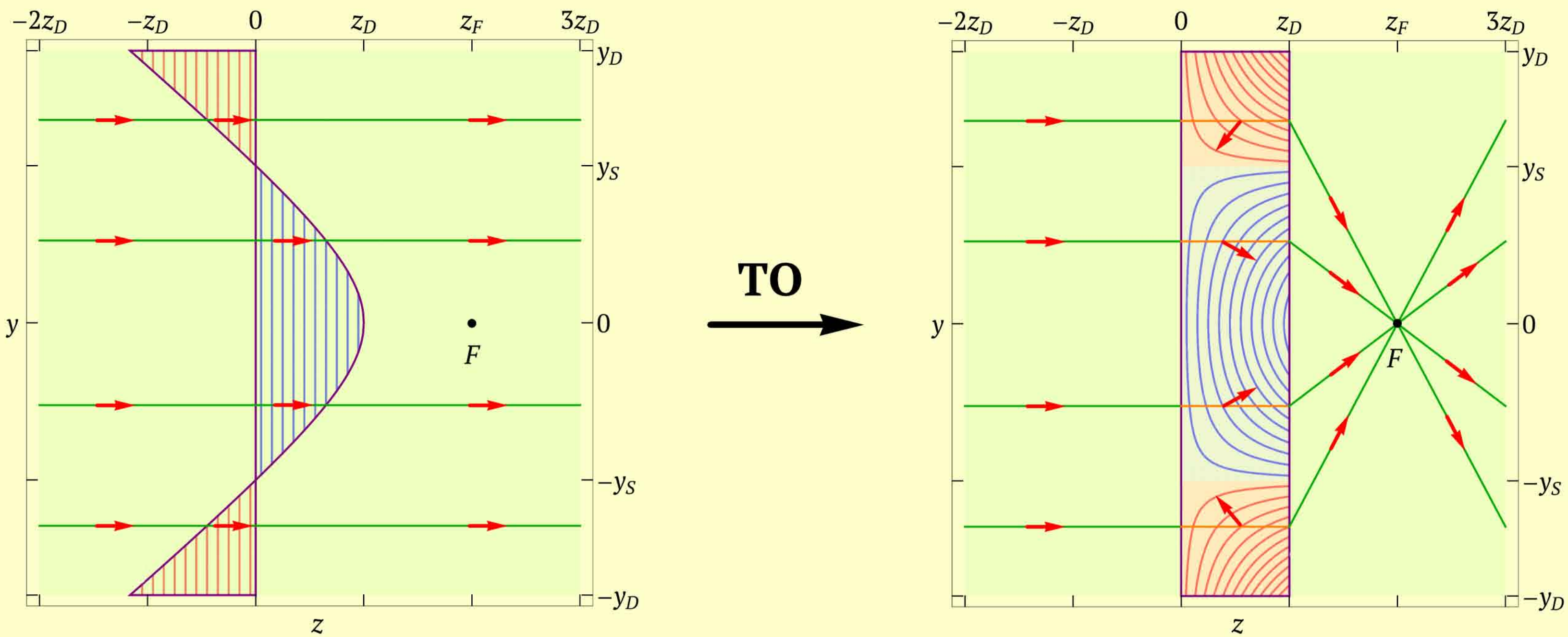
$$r|_{z=0}=0 \qquad r|_{z=z_D}\neq 0$$

$$t|_{z=0}=1 \qquad t|_{z=z_D}\neq 1$$

M. Giloan, Designing Devices for Wave-Vector Manipulation Using a Transformation-Optics Approach, Phys. Rev. Applied 8, 014005 (2017)

1) Flat lenses designed by transformation-optics

Converging lens – forward propagation (toward focal point)



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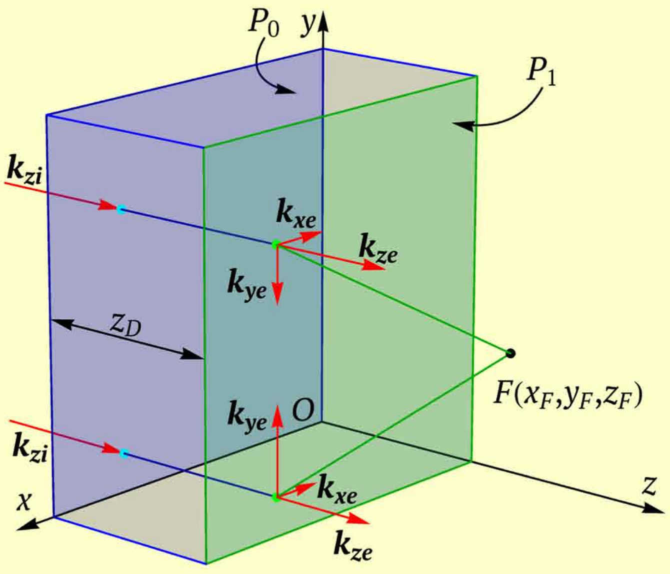
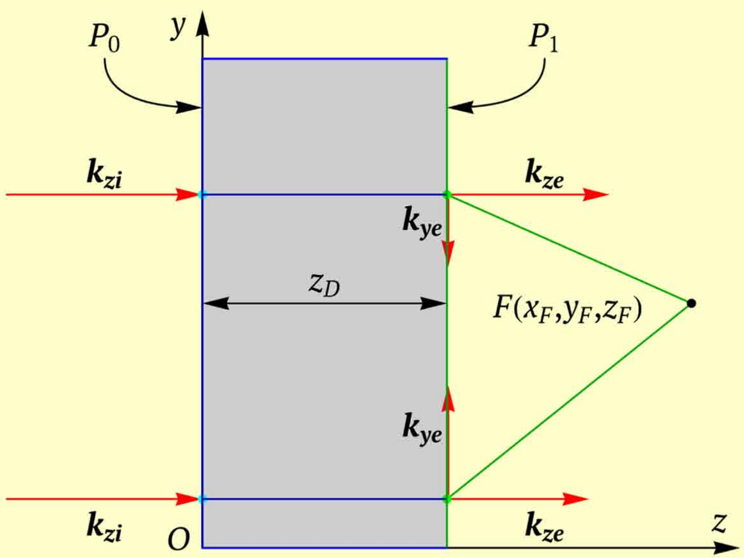
Wave vector manipulation





Transformation function retrieval

$$\frac{k_{xe}}{k_{ze}}=\frac{x-x_F}{z_D-z_F}$$

$$\frac{k_{ye}}{k_{ze}}=\frac{y-y_F}{z_D-z_F}$$

$$k_{xe}=z_D\cdot h_x$$

$$k_{ye}=z_D\cdot h_y$$

$$k_{xe}^2+k_{ye}^2+k_{ze}^2=1$$

$$h_x^2+h_y^2=\frac{1}{z_D^2}\cdot\frac{(x-x_F)^2+(y-y_F)^2}{\varphi^2+(x-x_F)^2+(y-y_F)^2}$$

$$h(x,y)=\frac{1}{f(x,y)}=\delta-\gamma\cdot\left(\varphi^2+(x-x_F)^2+(y-y_F)^2\right)^{1/2}$$

$\gamma=\pm 1/z_D$ $\quad f(x_F,y_F)=1 \longrightarrow \delta=1+\varphi/z_D$

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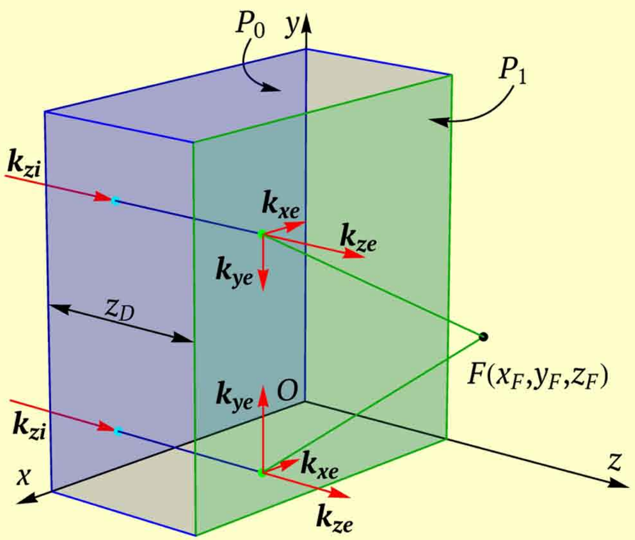
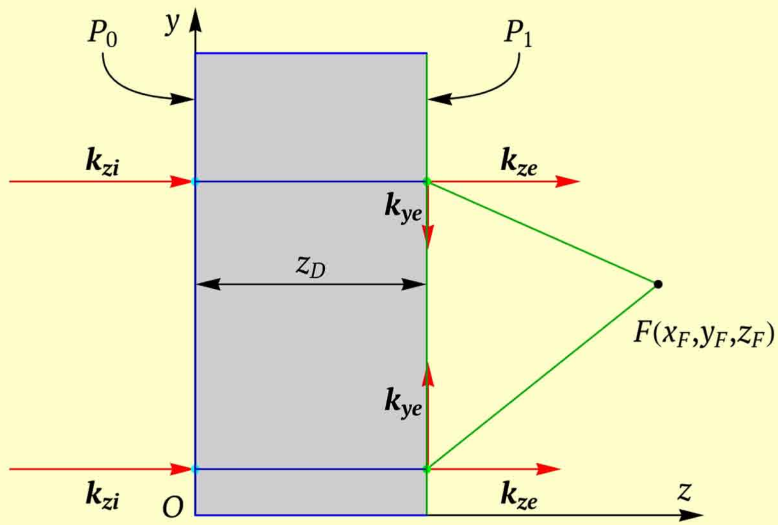
1) Flat lenses designed by transformation-optics

Devices for wave vector manipulation





$$\begin{cases} x \rightarrow x \\ y \rightarrow y \\ z \rightarrow z \cdot f(x,y) \end{cases}$$

$$h(x,y) = 1/f(x,y)$$

$$\begin{cases} x \rightarrow x \\ y \rightarrow y \\ z \rightarrow z/h(x,y) \end{cases}$$

Emergent wave at output interface (P_1: $z=z_D$)

$k_{x1} = z_D \cdot h_x$	$\longrightarrow$	$k_{xe} = z_D \cdot h_x$
$k_{y1} = z_D \cdot h_y$	$\longrightarrow$	$k_{ye} = z_D \cdot h_y$
$k_{z1} = h$	$k_{xe}^2 + k_{ye}^2 + k_{ze}^2 = 1 \longrightarrow$	k_{ze}

Constitutive parameters

$$\varepsilon = \mu = \begin{pmatrix} h & 0 & -z h_x \\ 0 & h & -z h_y \\ -z h_x & -z h_y & (g^2+1)/h \end{pmatrix}$$

$$g^2 = z^2 (h_x^2 + h_y^2)$$

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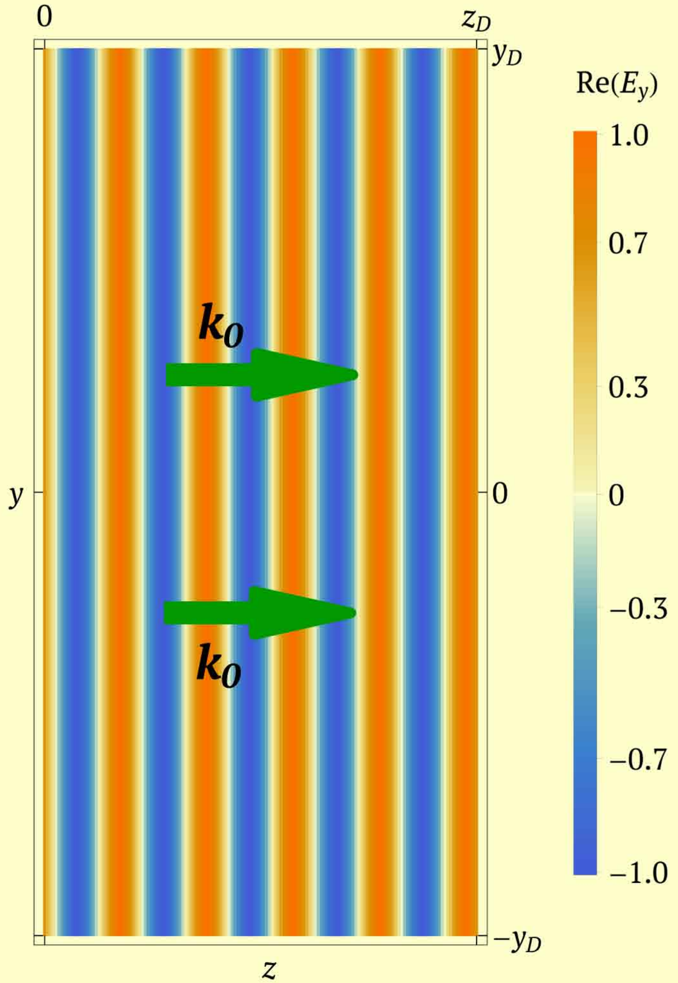
1) Flat lenses designed by transformation-optics

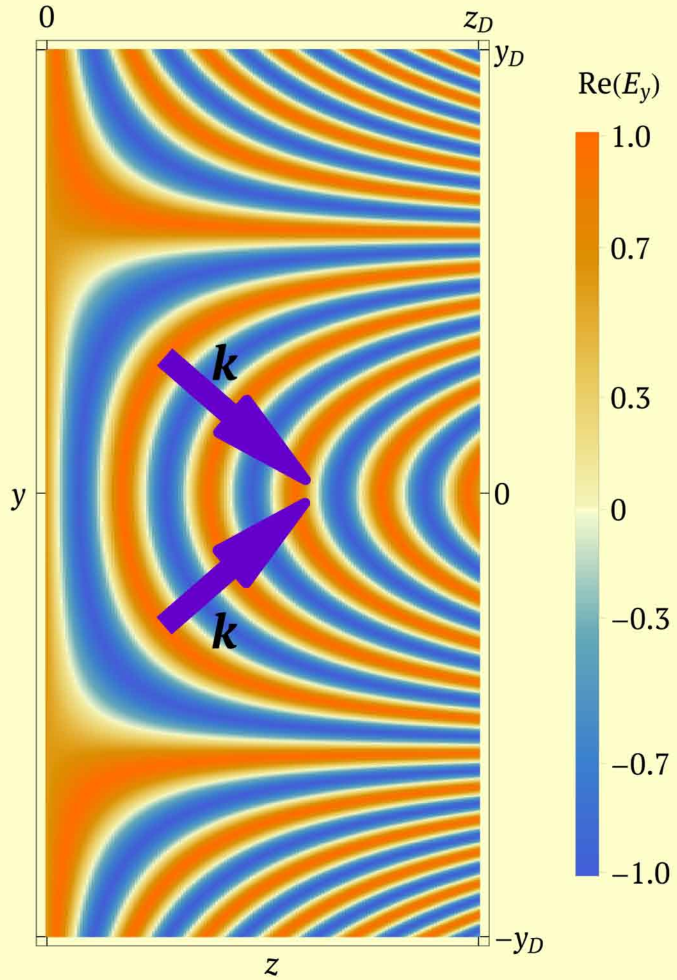
Initial space and field



Transformation

$$\begin{Bmatrix} x' = x \\ y' = y \\ z' = z \cdot f(x, y) \end{Bmatrix}$$

Transformed space and field



Designing devices for sub-wavelength imaging using a transformation-optics approach

1)Flat lenses designed by transformation-optics

2)Reflection and transmission of flat lenses media

3)Optical imaging devices based on flat lenses

Mircea Giloan, Robert Gutt and Gavril Saplacan

Company for Applied Informatics, Cluj-Napoca, Romania

Designing devices for sub-wavelength imaging using a transformation-optics approach

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