Coupled mode theory modeling of circular integrated optical microresonators

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http://www.math.utwente.nl/mpcm/aamp/Projects/Nais/

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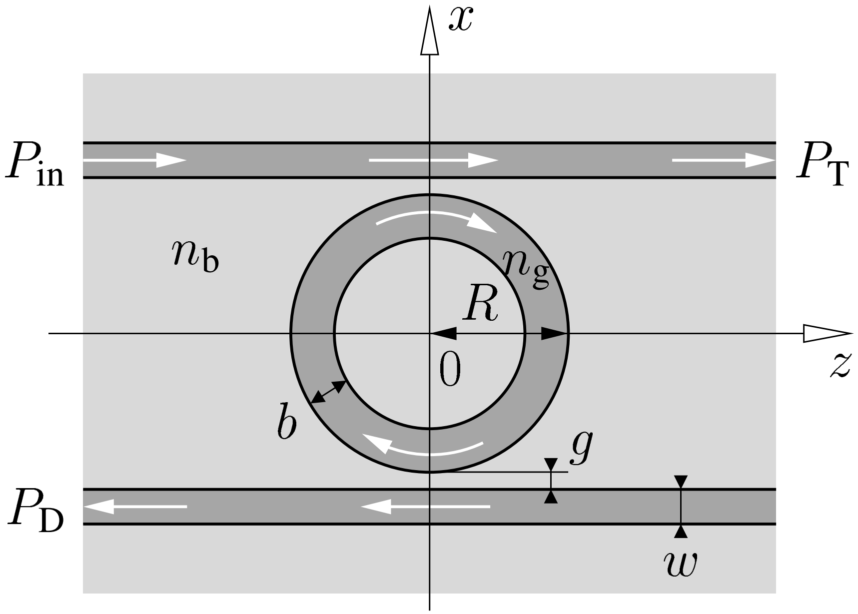
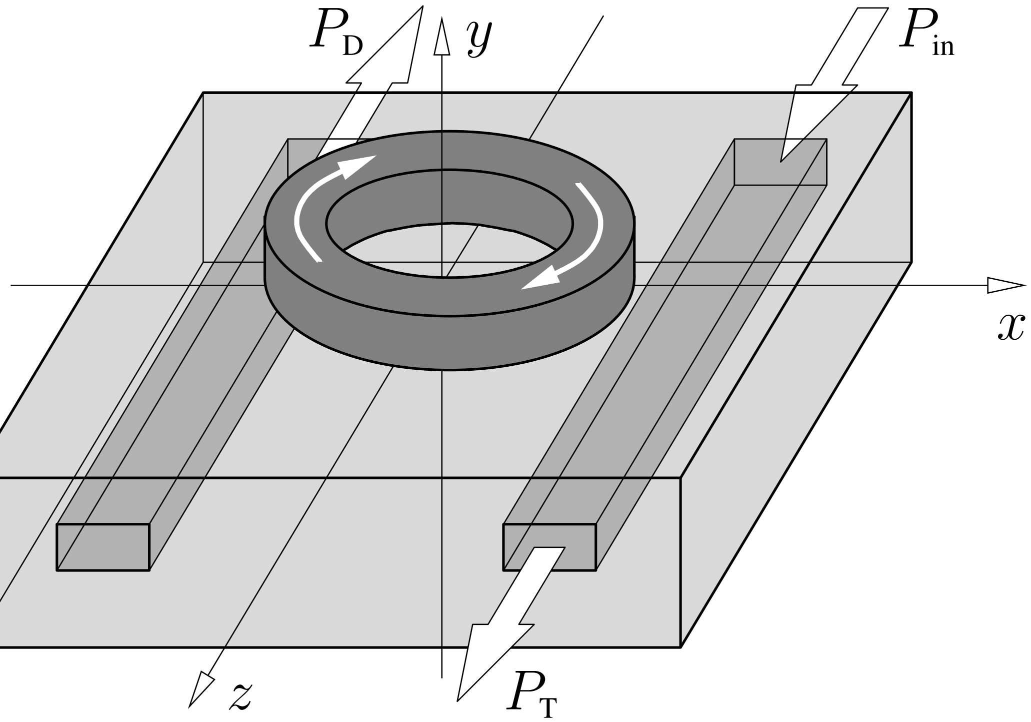
Circular integrated optical microresonators

(2-D)

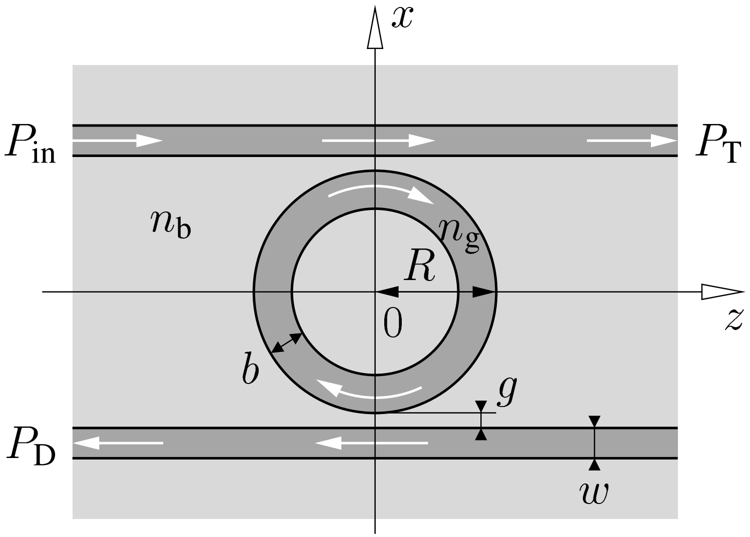


(3-D)



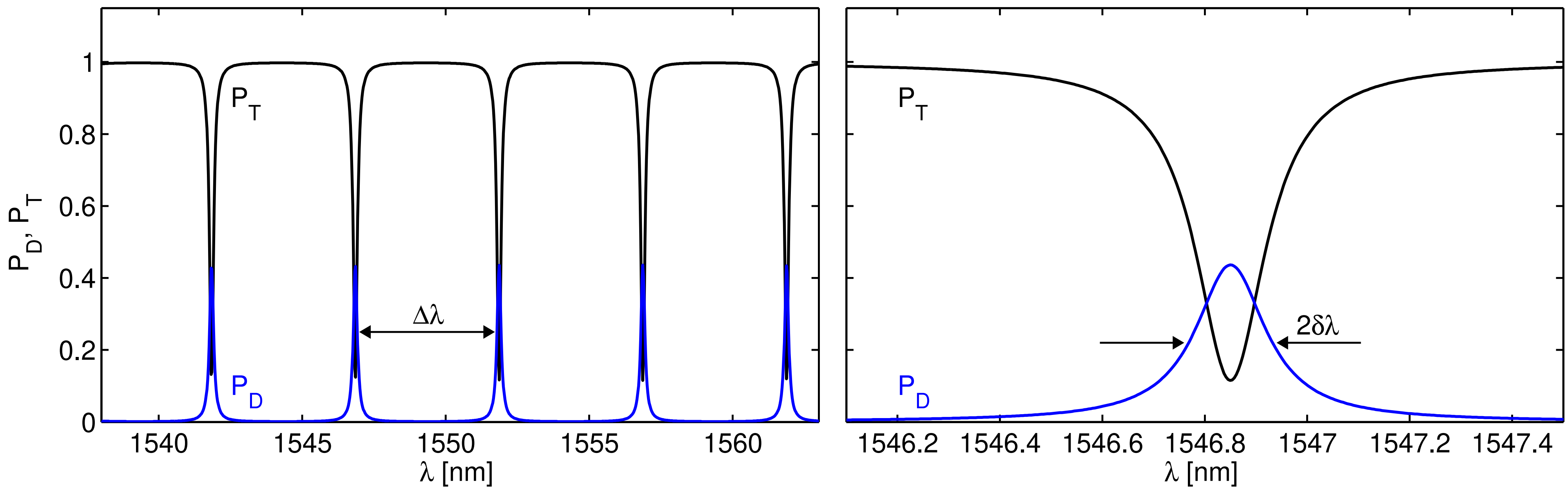
$$P_{\text{T}}(\lambda) = ?, \quad P_{\text{D}}(\lambda) = ?$$

Spectral response



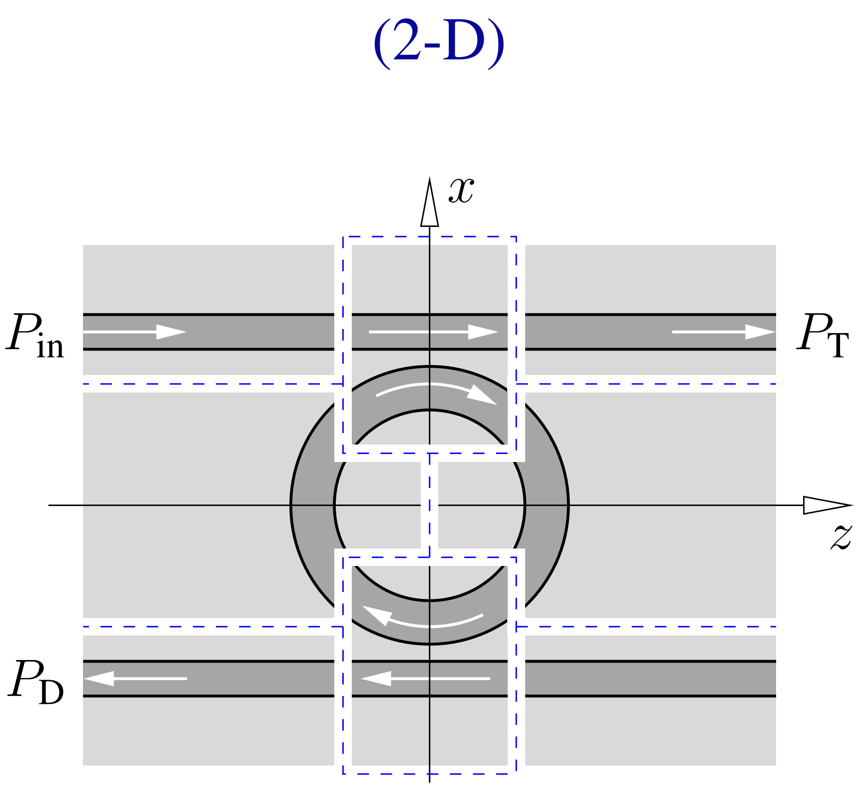
$R = 50\,\mu$m, $b = w = 1.0\,\mu$m, $g = 0.9\,\mu$m,
$n_b = 1.45$, $n_g = 1.60$; 2D, TE.

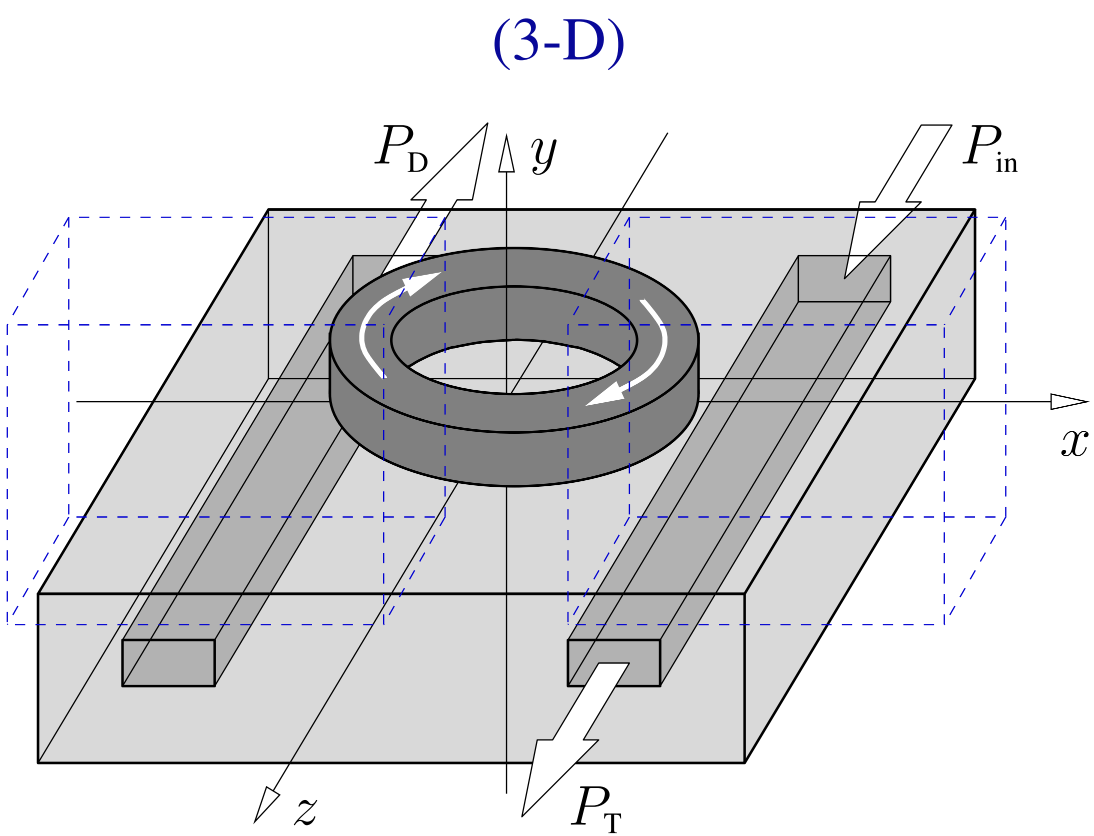
$\Delta\lambda = 5.0\,$nm, $2\delta\lambda = 0.17\,$nm,
$F = 30$, $Q = 9400$, $P_{D,res} = 0.44$.



Filter elements, building blocks for densely integrated optics.

Ringresonator modeling





- Ringresonator $\approx$ 2 couplers $+$ 2 cavity segments.
- CW description, $\boldsymbol{E}, \boldsymbol{H} \sim \mathrm{e}^{\mathrm{i}\omega t}$, $\omega = k\,\mathrm{c}$, $k = 2\pi/\lambda$; $\omega \in \mathbb{R}$, given.

Ab initio 2-D & 3-D simulations …

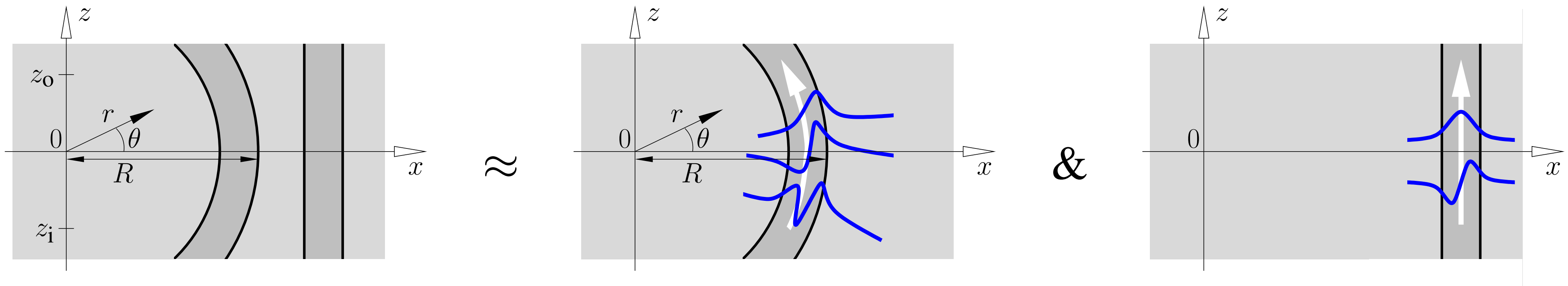
Outline

- CMT ringresonator model
  - Coupler modeling, basis fields, CMT ansatz
  - Coupled mode equations, solution
  - Resonator: power transmission, spectra

- 2-D modeling
  - Basis fields: analytical bend modes
  - Bent-straight waveguide couplers
  - Multimode microdisk resonator

- 3-D simulations
  - Vertically coupled microdisk-resonator
  - Resonator with “hybrid” ring-cavity

Coupler modeling



$\boldsymbol{E}, \boldsymbol{H}, \epsilon$ $\quad$ $\boldsymbol{E}_m, \boldsymbol{H}_m, \epsilon_m = \epsilon_\mathrm{b}$ $\quad$ $\boldsymbol{E}_m, \boldsymbol{H}_m, \epsilon_m = \epsilon_\mathrm{s}$

2-D basis fields, analytical:

- Cavity: 2-D (1-D) bend modes $\quad$ (ϵ_b)

$$\begin{pmatrix} \boldsymbol{E}_m \\ \boldsymbol{H}_m \end{pmatrix}(x, z) = \begin{pmatrix} \boldsymbol{E}_{m,0} \\ \boldsymbol{H}_{m,0} \end{pmatrix}(r(x, z))\, \mathrm{e}^{-\mathrm{i}\gamma_m R\theta(x,z)},$$

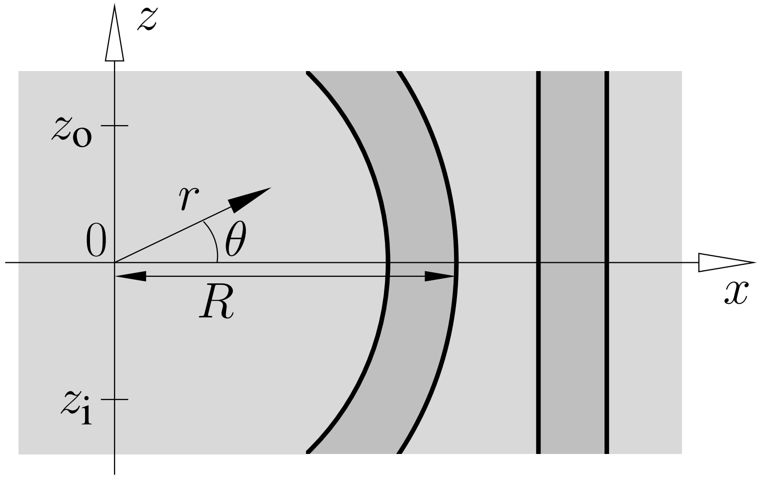
- Straight bus core: 2-D (1-D) guided modes $\quad$ (ϵ_s)

$$\begin{pmatrix} \boldsymbol{E}_m \\ \boldsymbol{H}_m \end{pmatrix}(x, z) = \begin{pmatrix} \boldsymbol{E}_{m,0} \\ \boldsymbol{H}_{m,0} \end{pmatrix}(x)\, \mathrm{e}^{-\mathrm{i}\beta_m z}.$$

Coupled mode ansatz: $\quad$ $C_m(z) = ?$

$$\begin{pmatrix} \boldsymbol{E} \\ \boldsymbol{H} \end{pmatrix}(x, z) = \sum_m C_m(z) \begin{pmatrix} \boldsymbol{E}_m \\ \boldsymbol{H}_m \end{pmatrix}(x, z), \qquad \begin{pmatrix} \boldsymbol{\mathcal{E}} \\ \boldsymbol{\mathcal{H}} \end{pmatrix}(x, z, t) = \frac{1}{2}\mathrm{Re} \begin{pmatrix} \boldsymbol{E} \\ \boldsymbol{H} \end{pmatrix}(x, z)\, \mathrm{e}^{\mathrm{i}\omega t}.$$

Coupled mode equations, derivation



Functional form of Maxwell equations:

$$\mathcal{F}(\boldsymbol{E},\boldsymbol{H}) = \iint \left(\boldsymbol{H}^*\cdot(\nabla\times\boldsymbol{E}) - \boldsymbol{E}^*\cdot(\nabla\times\boldsymbol{H}) + \mathrm{i}\omega\mu_0|\boldsymbol{H}|^2 + \mathrm{i}\omega\epsilon_0\epsilon|\boldsymbol{E}|^2\right)\,\mathrm{d}x\,\mathrm{d}z\,,$$

$$\{\delta_{\boldsymbol{E}}\mathcal{F} = 0\,,\ \ \delta_{\boldsymbol{H}}\mathcal{F} = 0\} \quad \leftrightsquigarrow \quad \{\nabla\times\boldsymbol{E} = -\mathrm{i}\omega\mu_0\boldsymbol{H}\,,\ \ \nabla\times\boldsymbol{H} = \mathrm{i}\omega\epsilon_0\epsilon\boldsymbol{E}\}\,.$$

$$\mathcal{F}(\boldsymbol{E},\boldsymbol{H}) \xrightarrow{\text{CMT ansatz}} \mathcal{F}(\boldsymbol{C})\,;$$

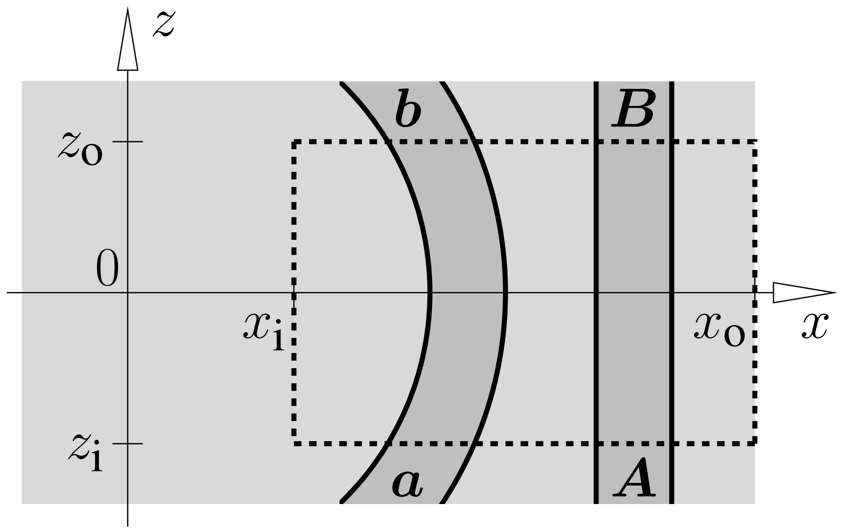
$$\delta_{\boldsymbol{C}}\mathcal{F} = 0 \qquad\qquad O_{lm} = \frac{1}{4}\int \boldsymbol{e}_z\cdot(\boldsymbol{E}_m\times\boldsymbol{H}_l^* + \boldsymbol{E}_l^*\times\boldsymbol{H}_m)\,\mathrm{d}x\,,$$

$$\mathsf{O}(z)\,\frac{\mathrm{d}}{\mathrm{d}z}\boldsymbol{C}(z) = \mathsf{K}(z)\,\boldsymbol{C}(z)\,, \qquad\qquad K_{lm} = -\mathrm{i}\,\frac{\omega\epsilon_0}{4}\int \boldsymbol{E}_l^*\cdot(\epsilon-\epsilon_m)\,\boldsymbol{E}_m\,\mathrm{d}x\,.$$

$$\mathsf{O}(z)\,\frac{\mathrm{d}}{\mathrm{d}z}\boldsymbol{C}(z) = \mathsf{K}(z)\,\boldsymbol{C}(z)\,,$$

$$O_{lm} = \frac{1}{4}\int \boldsymbol{e}_z\cdot(\boldsymbol{E}_m \times \boldsymbol{H}_l^* + \boldsymbol{E}_l^* \times \boldsymbol{H}_m)\,\mathrm{d}x\,,$$

$$K_{lm} = -\mathrm{i}\,\frac{\omega\epsilon_0}{4}\int \boldsymbol{E}_l^*\cdot(\epsilon - \epsilon_m)\,\boldsymbol{E}_m\,\mathrm{d}x\,.$$



Numerical solution $[z_\mathrm{i}, z_\mathrm{o}]$, projection $|_{z_\mathrm{i}}, |_{z_\mathrm{o}}$

Coupler scattering matrix S,

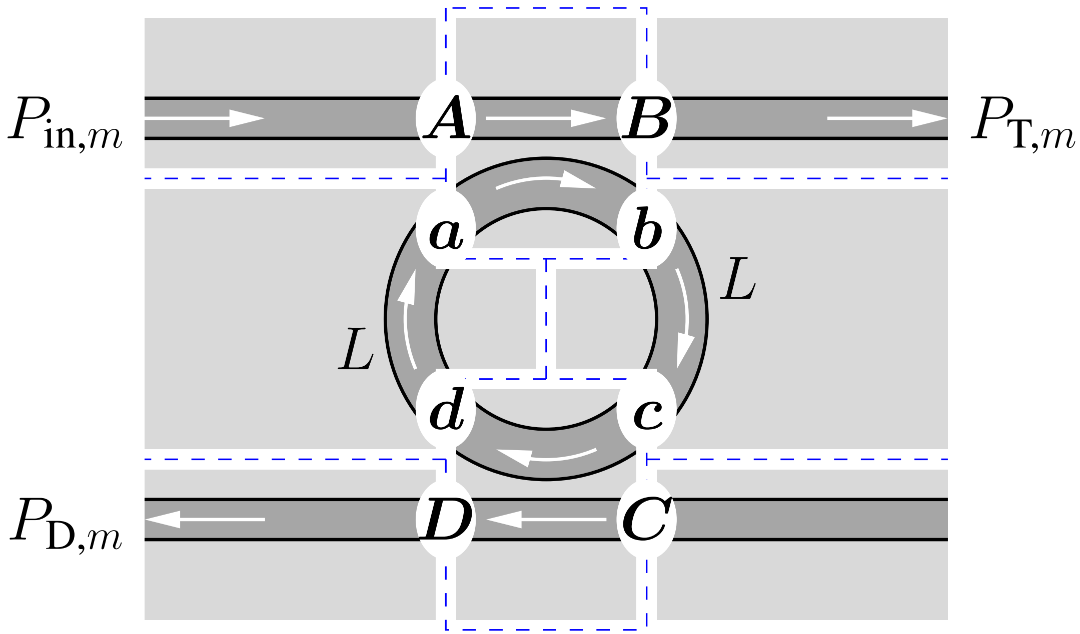
$$\begin{pmatrix}\boldsymbol{B}\\ \boldsymbol{b}\end{pmatrix} = \mathsf{S}\begin{pmatrix}\boldsymbol{A}\\ \boldsymbol{a}\end{pmatrix}, \qquad \sum_o |S_{o\,i}|^2 \le 1\,, \quad S_{o\,i} = S_{i\,o} \quad \left(\begin{array}{c}\text{normalized modes,}\\ \text{symmetric setting}\end{array}\right).$$

Resonator: power transmission, spectrum evaluation

$$\begin{pmatrix}\boldsymbol{B}\\ \boldsymbol{b}\end{pmatrix} = \begin{pmatrix}\mathsf{S}_{\mathrm{ss}} & \mathsf{S}_{\mathrm{sb}}\\ \mathsf{S}_{\mathrm{bs}} & \mathsf{S}_{\mathrm{bb}}\end{pmatrix}\begin{pmatrix}\boldsymbol{A}\\ \boldsymbol{a}\end{pmatrix},$$

$$\begin{pmatrix}\boldsymbol{D}\\ \boldsymbol{d}\end{pmatrix} = \begin{pmatrix}\mathsf{S}_{\mathrm{ss}} & \mathsf{S}_{\mathrm{sb}}\\ \mathsf{S}_{\mathrm{bs}} & \mathsf{S}_{\mathrm{bb}}\end{pmatrix}\begin{pmatrix}\boldsymbol{C}\\ \boldsymbol{c}\end{pmatrix},$$

$$\boldsymbol{c} = \mathsf{G}\boldsymbol{b}, \qquad \boldsymbol{a} = \mathsf{G}\boldsymbol{d}, \qquad \mathsf{G} = \mathrm{diag}\left(\mathrm{e}^{-\mathrm{i}\gamma_m L}\right).$$

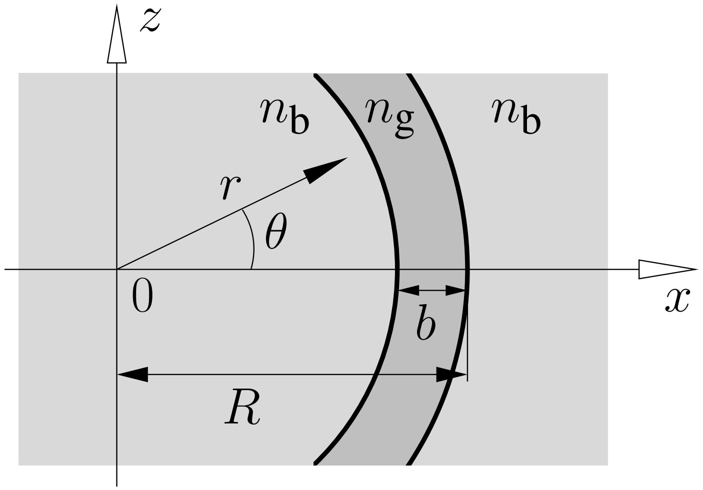


$P_{\mathrm{in},m}$, $\boldsymbol{A}$ given, $\boldsymbol{C} = 0$:

$$\begin{aligned}
\boldsymbol{b} &= \Omega^{-1}\mathsf{S}_{\mathrm{bs}}\boldsymbol{A}, & \Omega &= 1 - \mathsf{S}_{\mathrm{bb}}\mathsf{G}\mathsf{S}_{\mathrm{bb}}\mathsf{G}, & P_{\mathrm{D},m} &= |D_m|^2,\\
\boldsymbol{c} &= \mathsf{G}\Omega^{-1}\mathsf{S}_{\mathrm{bs}}\boldsymbol{A}, & & & P_{\mathrm{T},m} &= |B_m|^2,\\
\boldsymbol{d} &= \mathsf{S}_{\mathrm{bb}}\mathsf{G}\Omega^{-1}\mathsf{S}_{\mathrm{bs}}\boldsymbol{A}, & \boldsymbol{D} &= \mathsf{S}_{\mathrm{sb}}\mathsf{G}\Omega^{-1}\mathsf{S}_{\mathrm{bs}}\boldsymbol{A}, & &\\
\boldsymbol{a} &= \mathsf{G}\mathsf{S}_{\mathrm{bb}}\mathsf{G}\Omega^{-1}\mathsf{S}_{\mathrm{bs}}\boldsymbol{A}, & \boldsymbol{B} &= (\mathsf{S}_{\mathrm{sb}}\mathsf{G}\mathsf{S}_{\mathrm{bb}}\mathsf{G}\Omega^{-1}\mathsf{S}_{\mathrm{bs}} + \mathsf{S}_{\mathrm{ss}})\boldsymbol{A}. & &
\end{aligned}$$

Spectrum: $\mathsf{S}(\cancel{\lambda})_{L\to 2\pi R/2}$, $\gamma_m(\lambda)$ interpolated $\rightsquigarrow$ $P_{\mathrm{T},m}(\lambda)$, $P_{\mathrm{D},m}(\lambda)$.

2-D basis fields, bend mode analysis



Homogeneity along θ $\rightsquigarrow$ bend mode ansatz

$$\begin{pmatrix}\boldsymbol{\mathcal{E}}\\ \boldsymbol{\mathcal{H}}\end{pmatrix}(r,\theta,t) = \frac{1}{2}\mathrm{Re}\begin{pmatrix}\boldsymbol{E}_0\\ \boldsymbol{H}_0\end{pmatrix}(r)\,\mathrm{e}^{\mathrm{i}\omega t\,-\,\mathrm{i}\gamma R\theta},$$

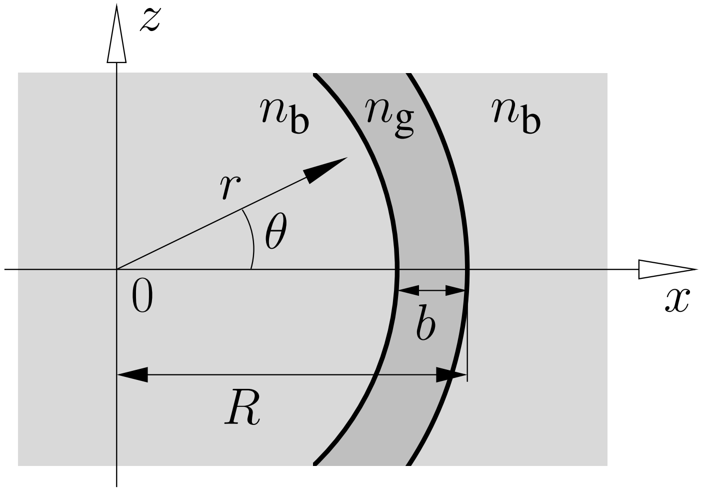
profile $\boldsymbol{E}_0$, $\boldsymbol{H}_0$,
propagation constant $\gamma = \beta - \mathrm{i}\alpha$.

$$\frac{\mathrm{d}^2\phi}{\mathrm{d}r^2} + \frac{1}{r}\frac{\mathrm{d}\phi}{\mathrm{d}r} + \left(k^2n^2 - \frac{\gamma^2R^2}{r^2}\right)\phi = 0\,,$$

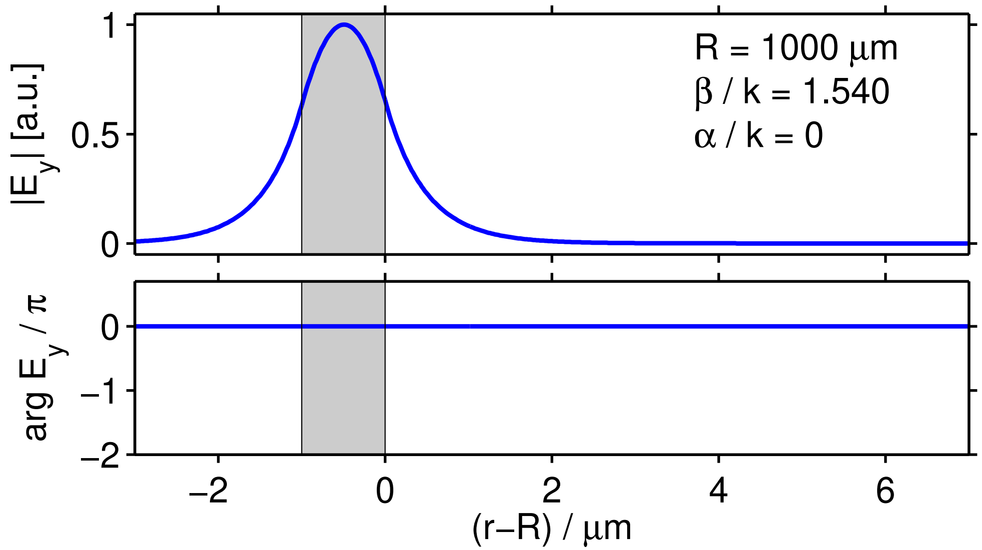
$n(r)$ piecewise constant, $\quad \phi = E_{0,y}$ (TE), $\quad \phi = H_{0,y}$ (TM).

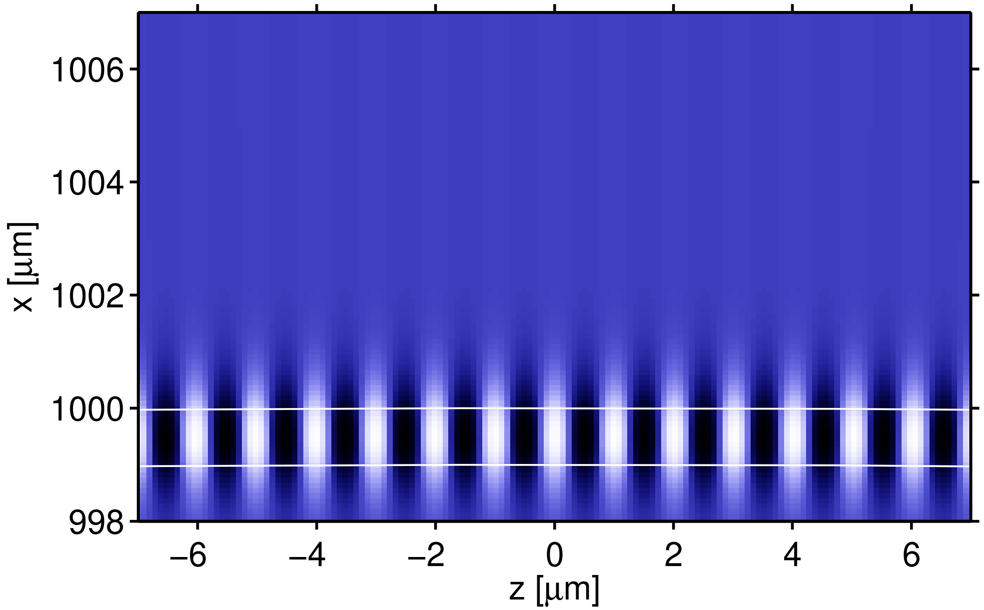
Bend modes :
- Nonzero solutions,
- bounded at the origin, $\sim J_{\gamma R}(n_\mathrm{b}kr)$ for $r < R - b$,
- outgoing exterior fields, $\sim H^{(2)}_{\gamma R}(n_\mathrm{b}kr)$ for $r > R$,
- continuity at interfaces : ϕ & $\mathrm{d}_r\phi$ (TE), ϕ & $(\mathrm{d}_r\phi)/n^2$ (TM).

Bend modes, examples

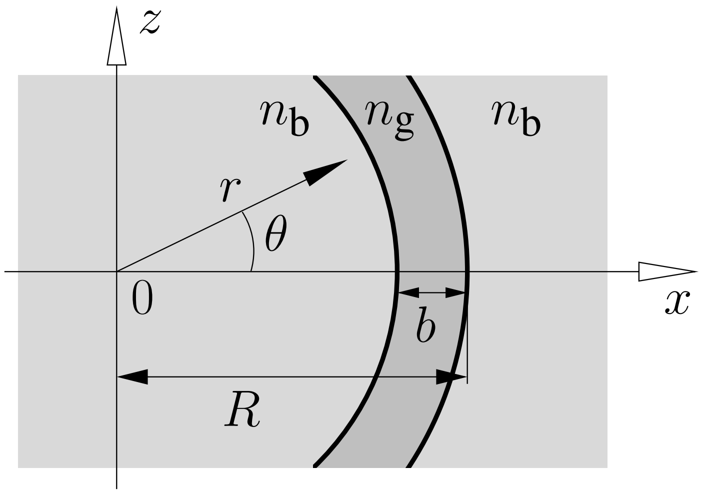


2D, TE,
$n_b = 1.45,\ n_g = 1.60,\ b = 1.0\,\mu\text{m},\ \lambda = 1.55\,\mu\text{m},$
$R = 1000\,\mu\text{m}.$

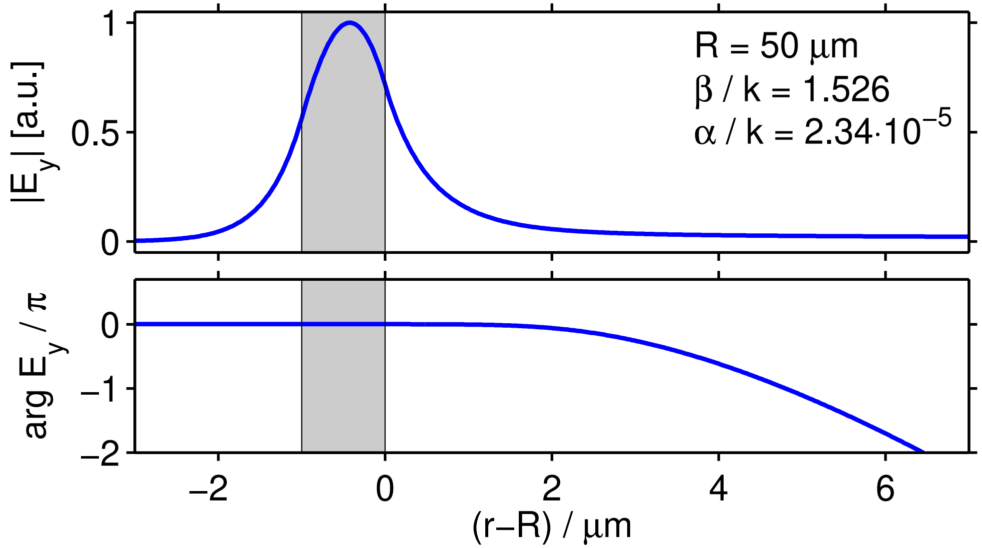


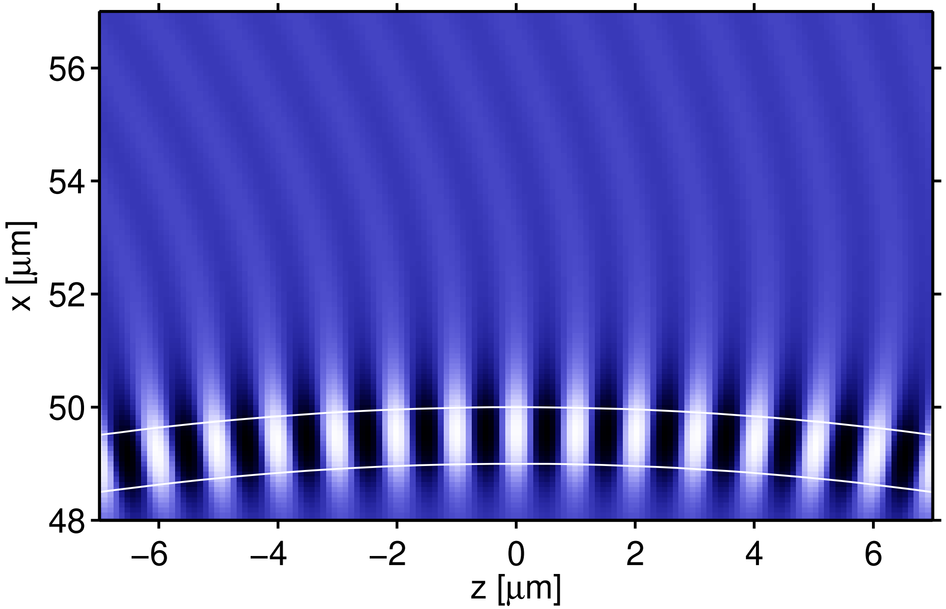


Bend modes, examples

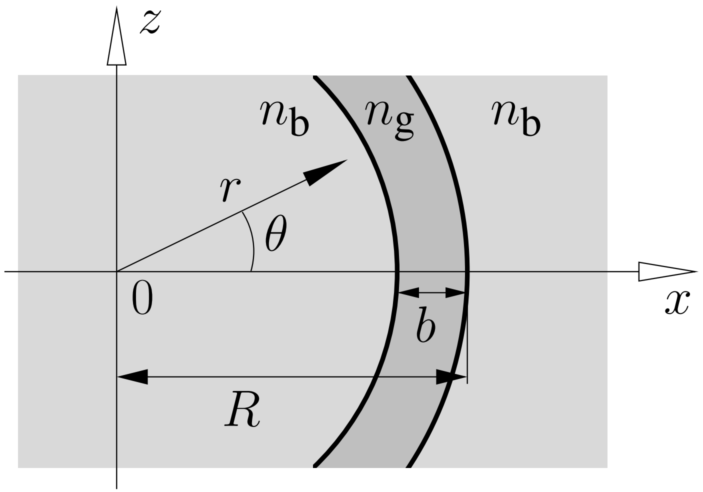


2D, TE,
$n_\mathrm{b} = 1.45,\ n_\mathrm{g} = 1.60,\ b = 1.0\,\mu\mathrm{m},\ \lambda = 1.55\,\mu\mathrm{m},$
$R = 50\,\mu\mathrm{m}.$

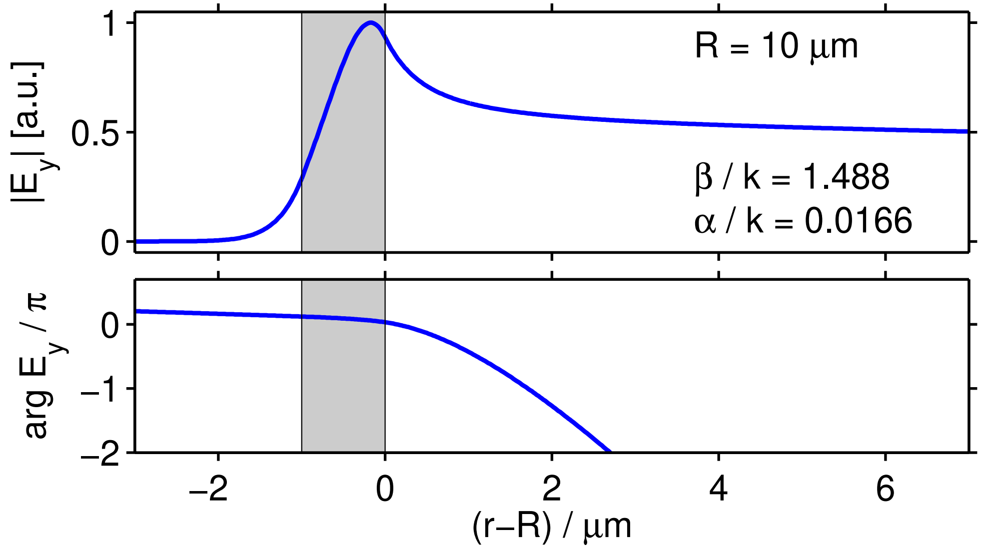


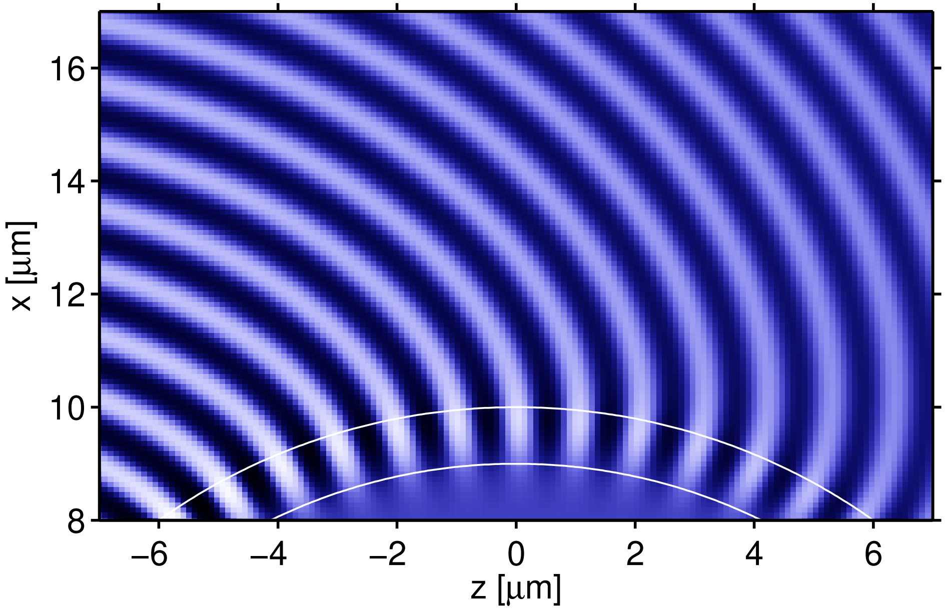


Bend modes, examples

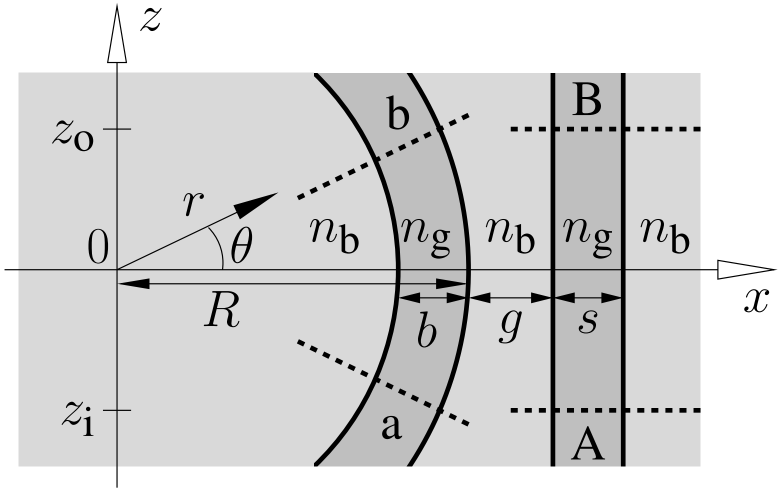


2D, TE,
$n_b = 1.45,\ n_g = 1.60,\ b = 1.0\,\mu\text{m},\ \lambda = 1.55\,\mu\text{m},$
$R = 10\,\mu\text{m}.$

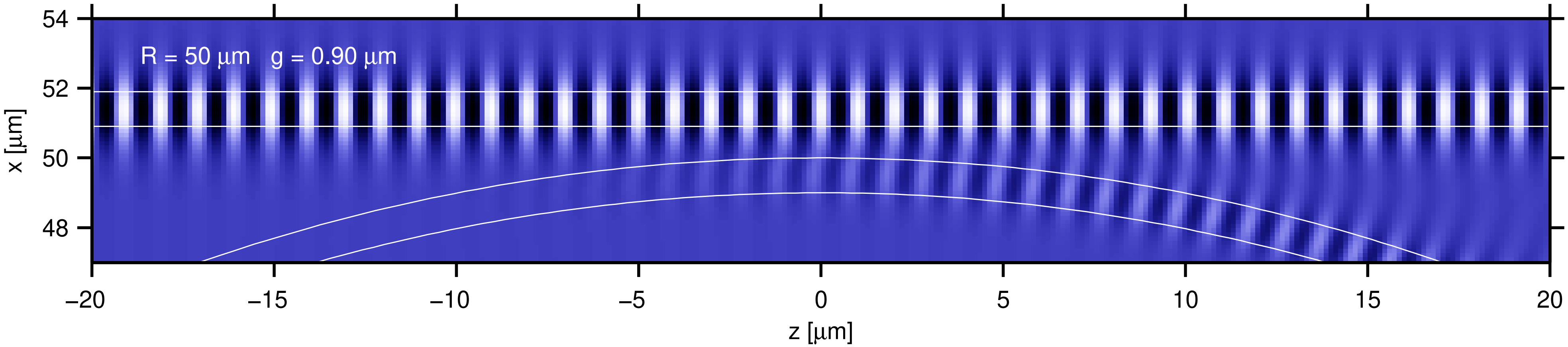




CMT coupler model, 2-D examples

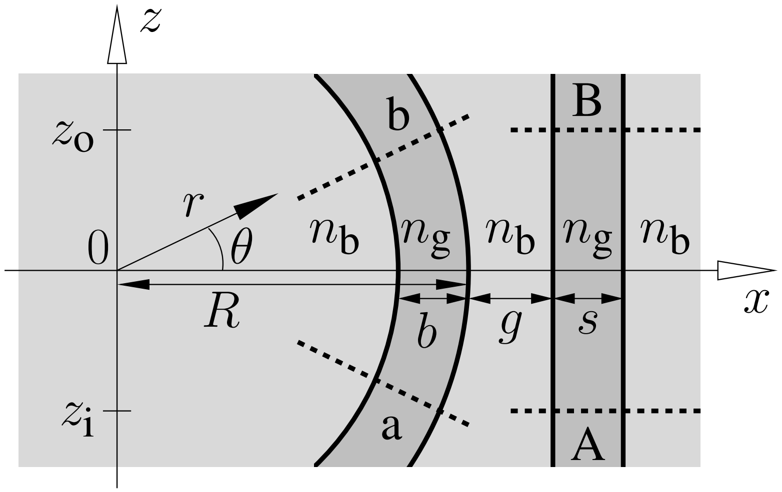


2D, TE,
$n_b = 1.45,\ n_g = 1.60,\ b = s = 1.0\,\mu\text{m},\ \lambda = 1.55\,\mu\text{m},$
$R = 50\,\mu\text{m},\ g = 0.90\,\mu\text{m}.$

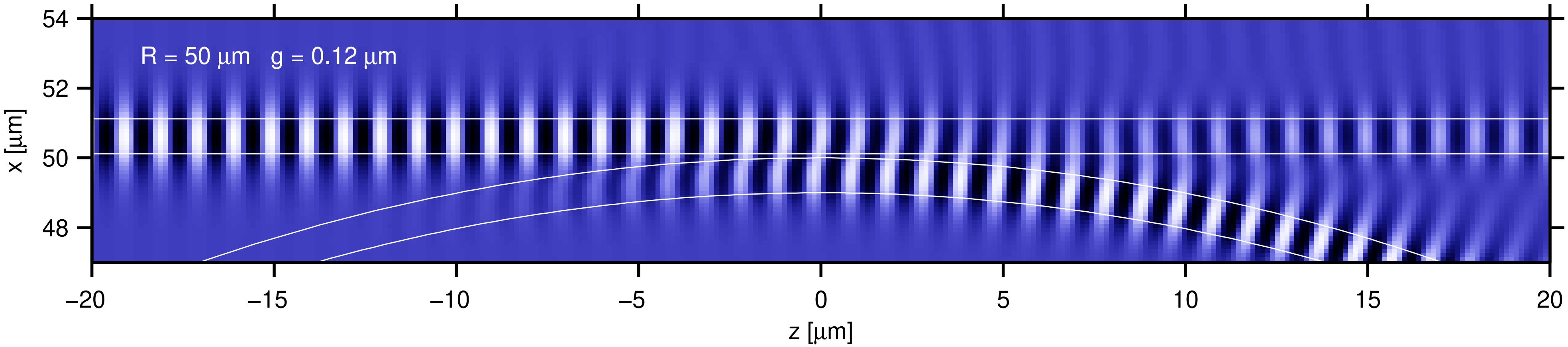


$$|S_{\mathrm{s\,s}}|^2 = 0.93,\ |S_{\mathrm{s\,b}}|^2 = |S_{\mathrm{b\,s}}|^2 = 0.07,\ |S_{\mathrm{b\,b}}|^2 = 0.92.$$

CMT coupler model, 2-D examples

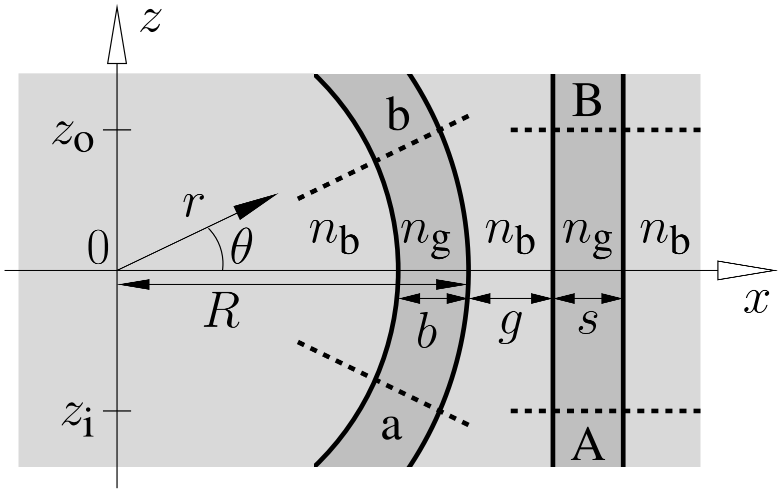


2D, TE,
$n_{\mathrm{b}} = 1.45,\ n_{\mathrm{g}} = 1.60,\ b = s = 1.0\,\mu\mathrm{m},\ \lambda = 1.55\,\mu\mathrm{m},$
$R = 50\,\mu\mathrm{m},\ g = 0.12\,\mu\mathrm{m}.$

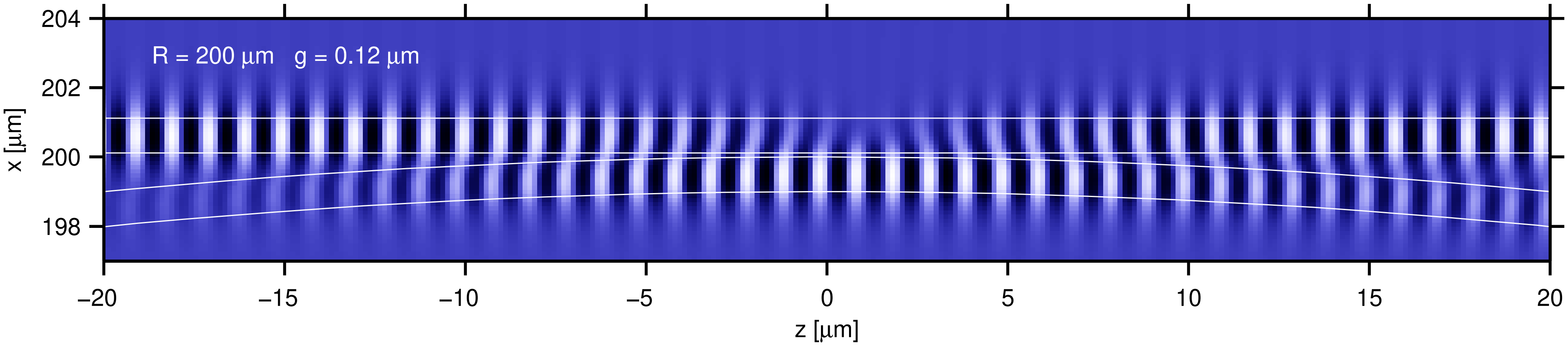


$$|S_{\mathrm{s\,s}}|^2 = 0.16,\ |S_{\mathrm{s\,b}}|^2 = |S_{\mathrm{b\,s}}|^2 = 0.83,\ |S_{\mathrm{b\,b}}|^2 = 0.16.$$

CMT coupler model, 2-D examples

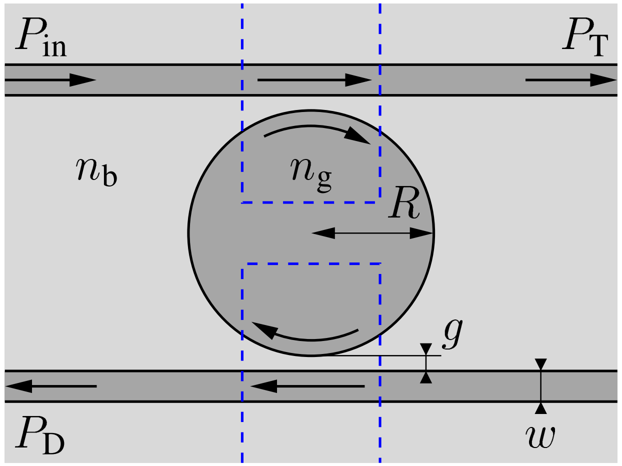


2D, TE,
$n_b = 1.45,\ n_g = 1.60,\ b = s = 1.0\,\mu$m, $\lambda = 1.55\,\mu$m,
$R = 200\,\mu$m, $g = 0.12\,\mu$m.



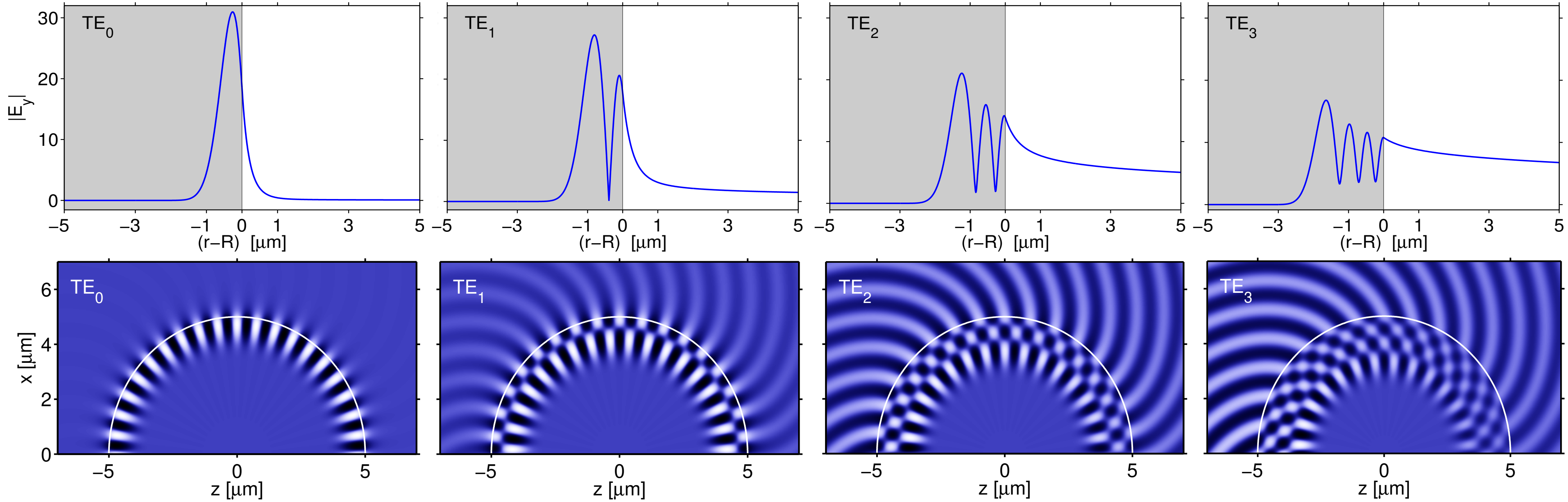
$$|S_{s\,s}|^2 = 0.93,\ |S_{s\,b}|^2 = |S_{b\,s}|^2 = 0.07,\ |S_{b\,b}|^2 = 0.93.$$

2-D microdisk, structure & basis fields

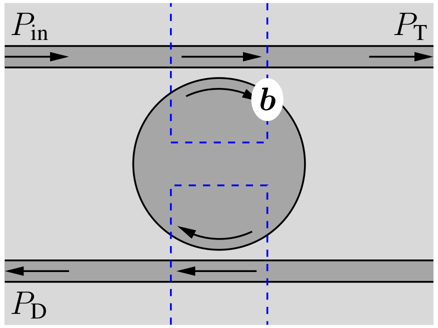


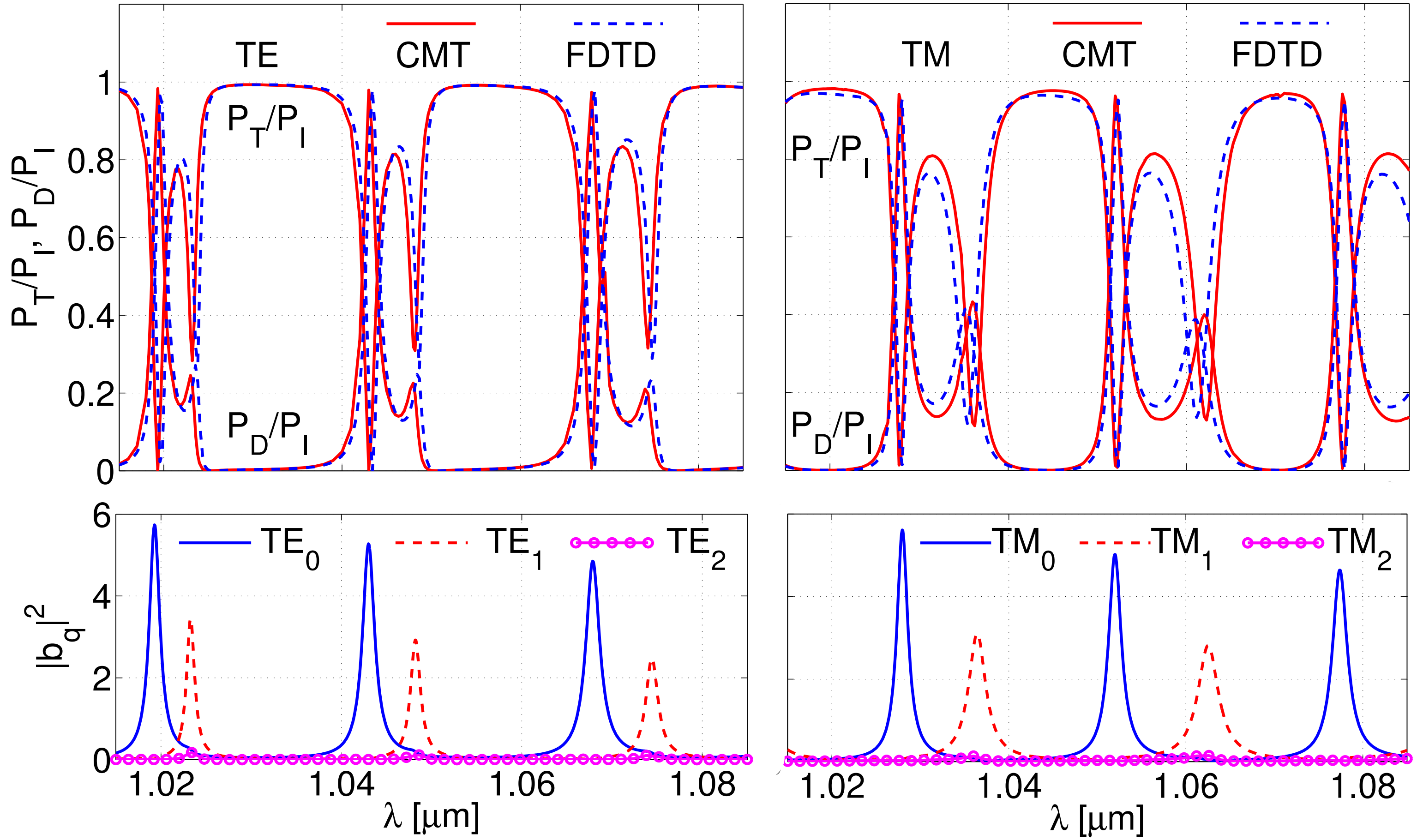
$n_{\mathrm{b}} = 1.0,\ n_{\mathrm{g}} = 1.5,$
$w = 0.4\,\mu\mathrm{m},\ g = 0.2\,\mu\mathrm{m},$
$R = 5.0\,\mu\mathrm{m}.$

Basis fields, cavity:

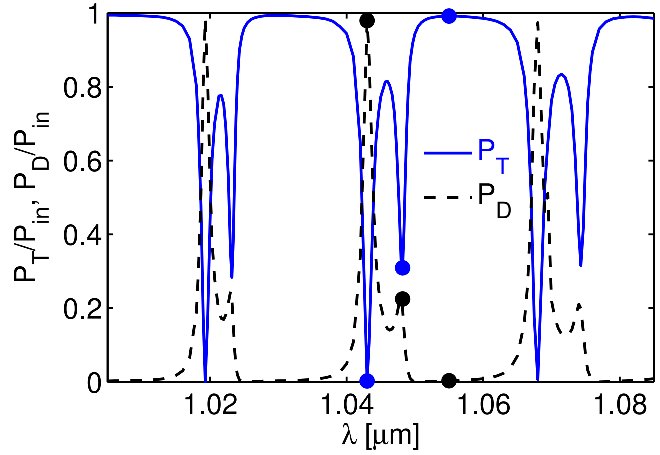


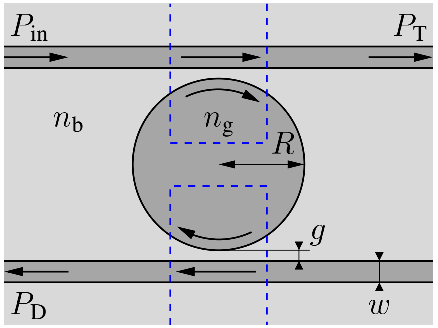
2-D microdisk, CMT & FDTD spectra

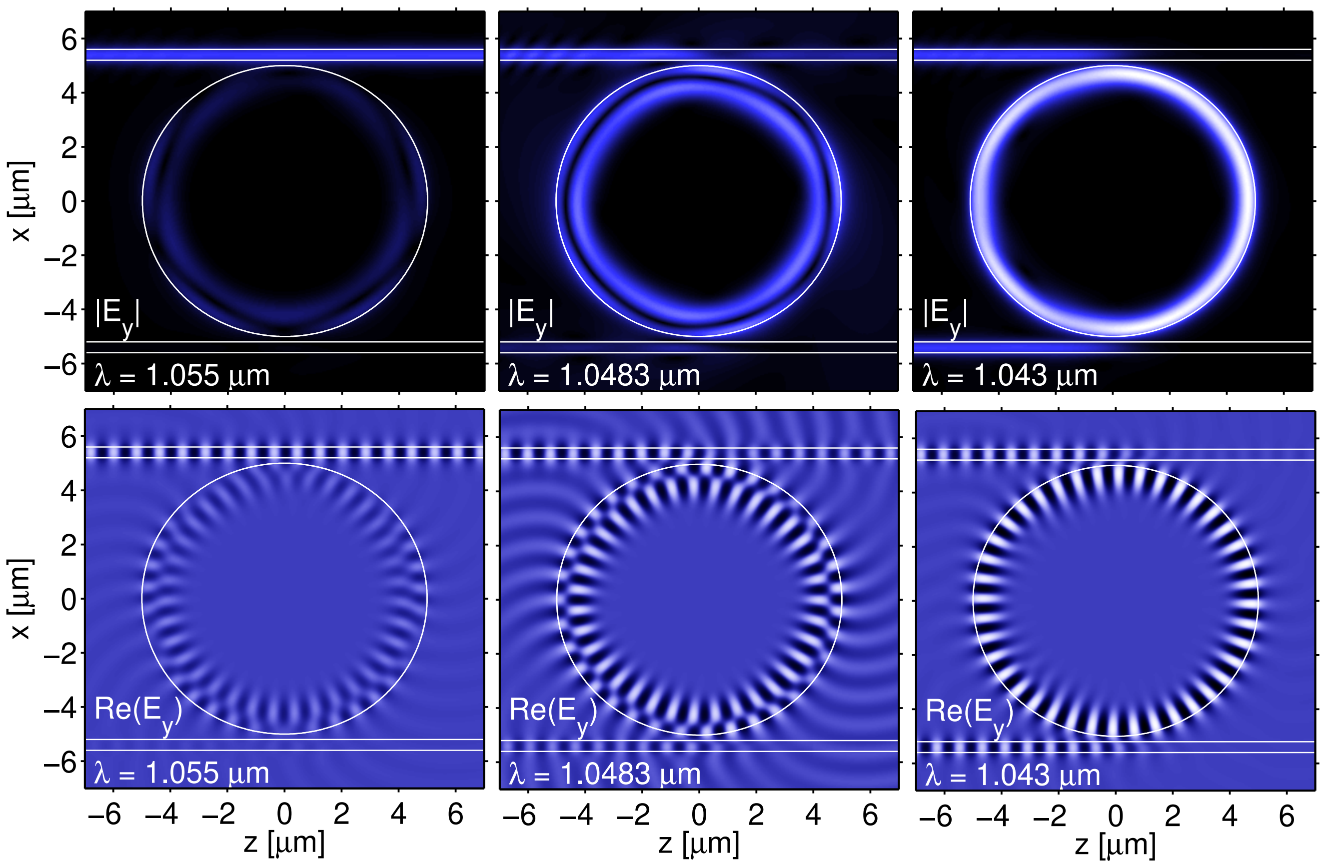




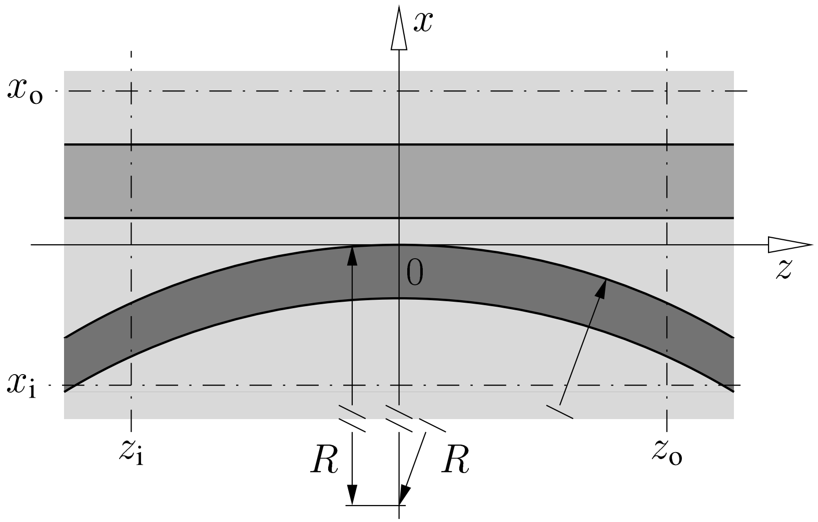
2-D microdisk, resonances

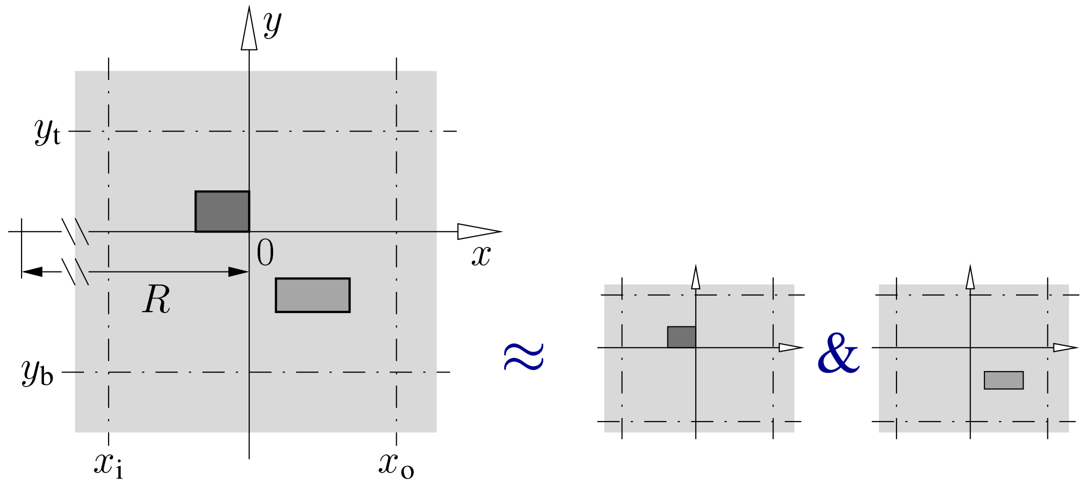






3-D coupler modeling





Numerical basis fields:

- Cavity: 3-D (2-D) bend modes (ϵ_{b})

$$\begin{pmatrix} \boldsymbol{E}_m \\ \boldsymbol{H}_m \end{pmatrix}(x,y,z) = \begin{pmatrix} \boldsymbol{E}_{m,0} \\ \boldsymbol{H}_{m,0} \end{pmatrix}(r(x,z),y)\,\mathrm{e}^{-\mathrm{i}\gamma_m R\theta(x,z)},$$

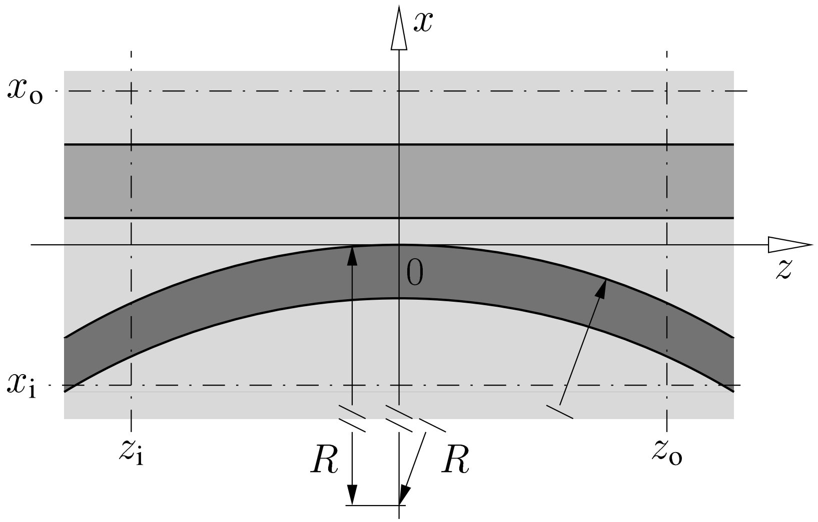
- Straight bus core: 3-D (2-D) guided modes (ϵ_{s})

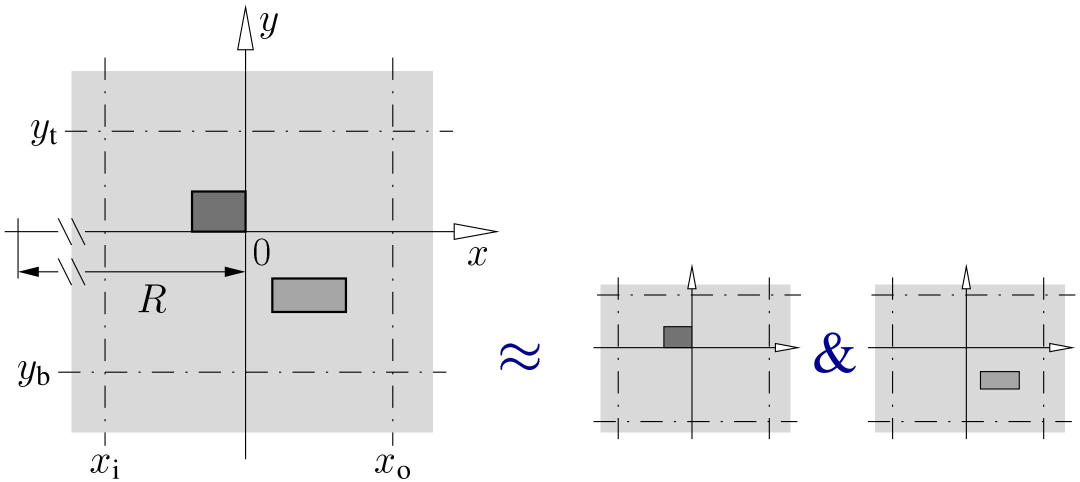
$$\begin{pmatrix} \boldsymbol{E}_m \\ \boldsymbol{H}_m \end{pmatrix}(x,y,z) = \begin{pmatrix} \boldsymbol{E}_{m,0} \\ \boldsymbol{H}_{m,0} \end{pmatrix}(x,y)\,\mathrm{e}^{-\mathrm{i}\beta_m z}.$$

Coupled mode ansatz:

$$\begin{pmatrix} \boldsymbol{\mathcal{E}} \\ \boldsymbol{\mathcal{H}} \end{pmatrix}(x,y,z,t) = \frac{1}{2}\mathrm{Re}\sum_m C_m(z)\begin{pmatrix} \boldsymbol{E}_m \\ \boldsymbol{H}_m \end{pmatrix}(x,y,z)\,\mathrm{e}^{\mathrm{i}\omega t}.$$

3-D CMT equations, solution





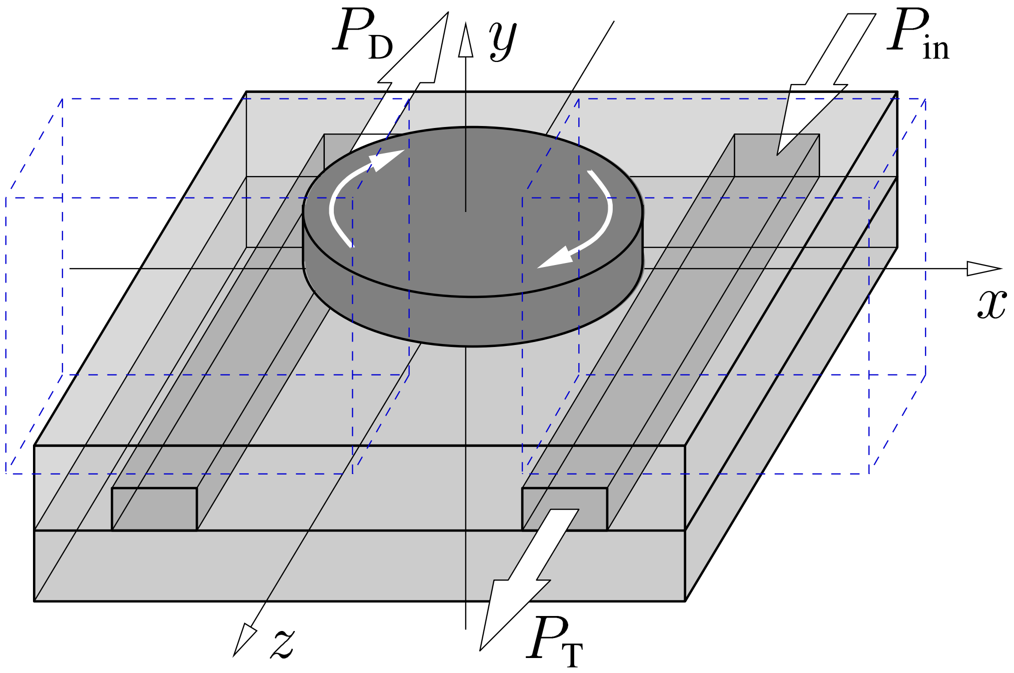
$$\mathsf{O}(z)\,\frac{\mathrm{d}}{\mathrm{d}z}\boldsymbol{C}(z) = \mathsf{K}(z)\,\boldsymbol{C}(z)\,, \qquad K_{lm} = -\mathrm{i}\,\frac{\omega\epsilon_0}{4}\iint \boldsymbol{E}_l^*\cdot(\epsilon-\epsilon_m)\,\boldsymbol{E}_m\,\mathrm{d}x\,\mathrm{d}y\,,$$

$$O_{lm} = \frac{1}{4}\iint \boldsymbol{e}_z\cdot(\boldsymbol{E}_m\times\boldsymbol{H}_l^* + \boldsymbol{E}_l^*\times\boldsymbol{H}_m)\,\mathrm{d}x\,\mathrm{d}y\,.$$

Numerical solution $[z_i, z_o]$, projection $|_{z_i}$, $|_{z_o}$

$\hookrightarrow$ S.

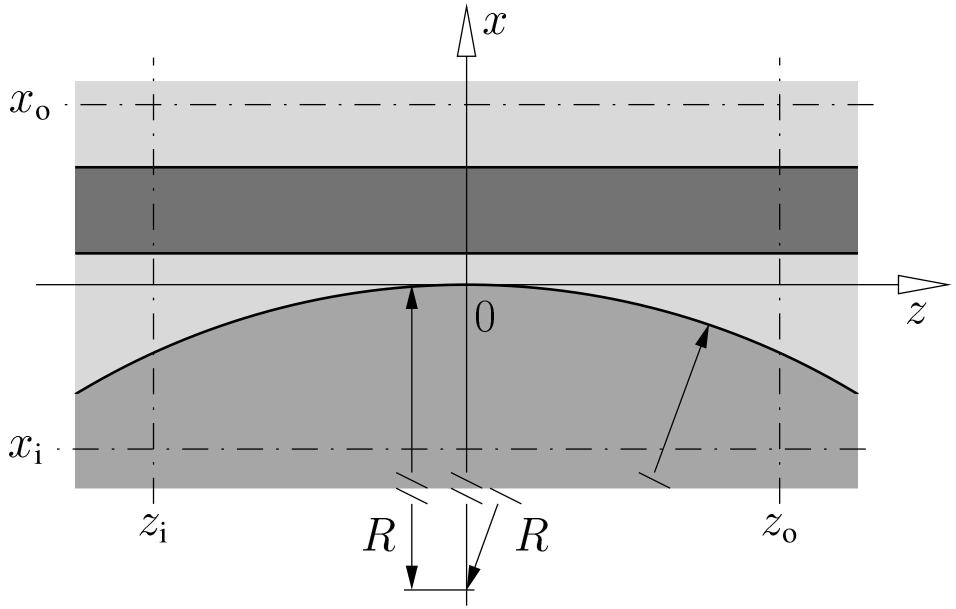
Vertically coupled multimode microdisk-resonator

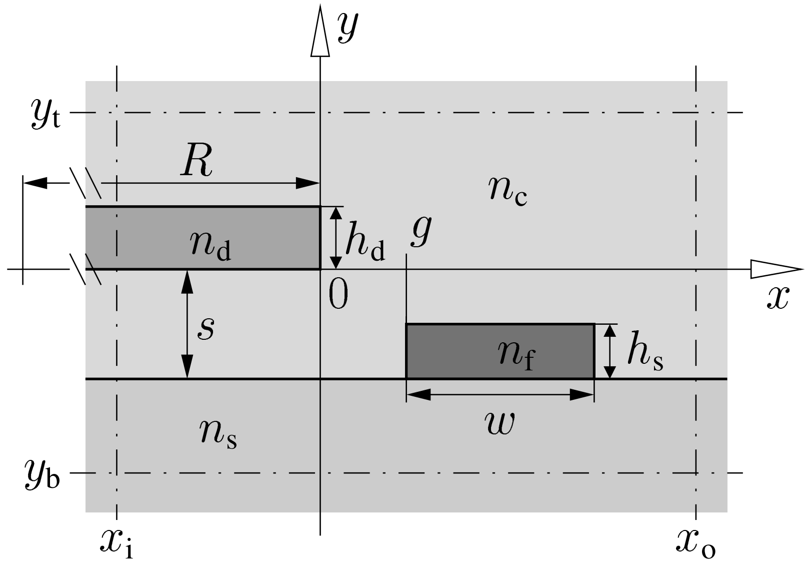


$w = 2.0\,\mu$m, $h_s = 140$ nm,
$n_f = 1.98$, $n_s = 1.45$,
$n_c = 1.4017$, $n_d = 1.6062$,
$h_d = 1.0\,\mu$m, $R = 100\,\mu$m;

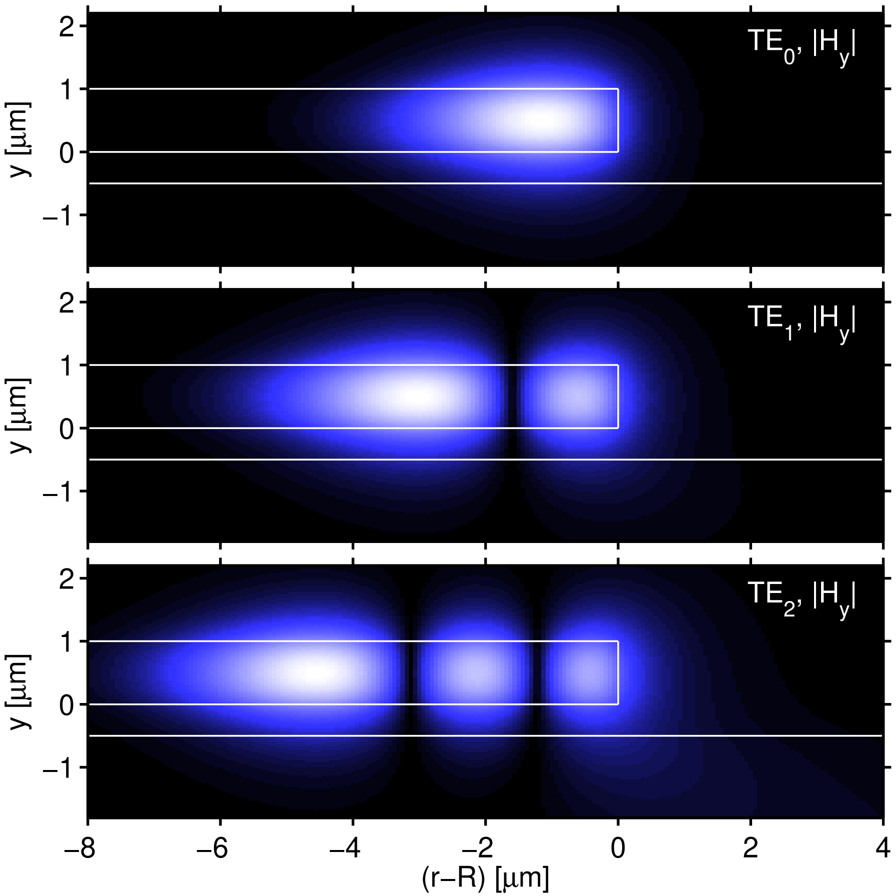
varying g, s;
target wavelength: $\lambda = 1.55\,\mu$m.

CMT computational window:
$[x_i, x_o] = [-12, 4]\,\mu$m,
$[y_b, y_t] = [-4, 4]\,\mu$m $- s$,
$[z_i, z_o] = [-30, 30]\,\mu$m.





Vertical straight-disk-coupler, CMT basis fields



$s = 0.5\,\mu$m

Cavity disk:
three TE-like bend modes,

	n_{eff}
b0, TE$_0$	$1.503778 - \mathrm{i}\,1.35 \cdot 10^{-9}$
b1, TE$_1$	$1.474931 - \mathrm{i}\,1.77 \cdot 10^{-6}$
b2, TE$_2$	$1.451487 - \mathrm{i}\,5.05 \cdot 10^{-5}$

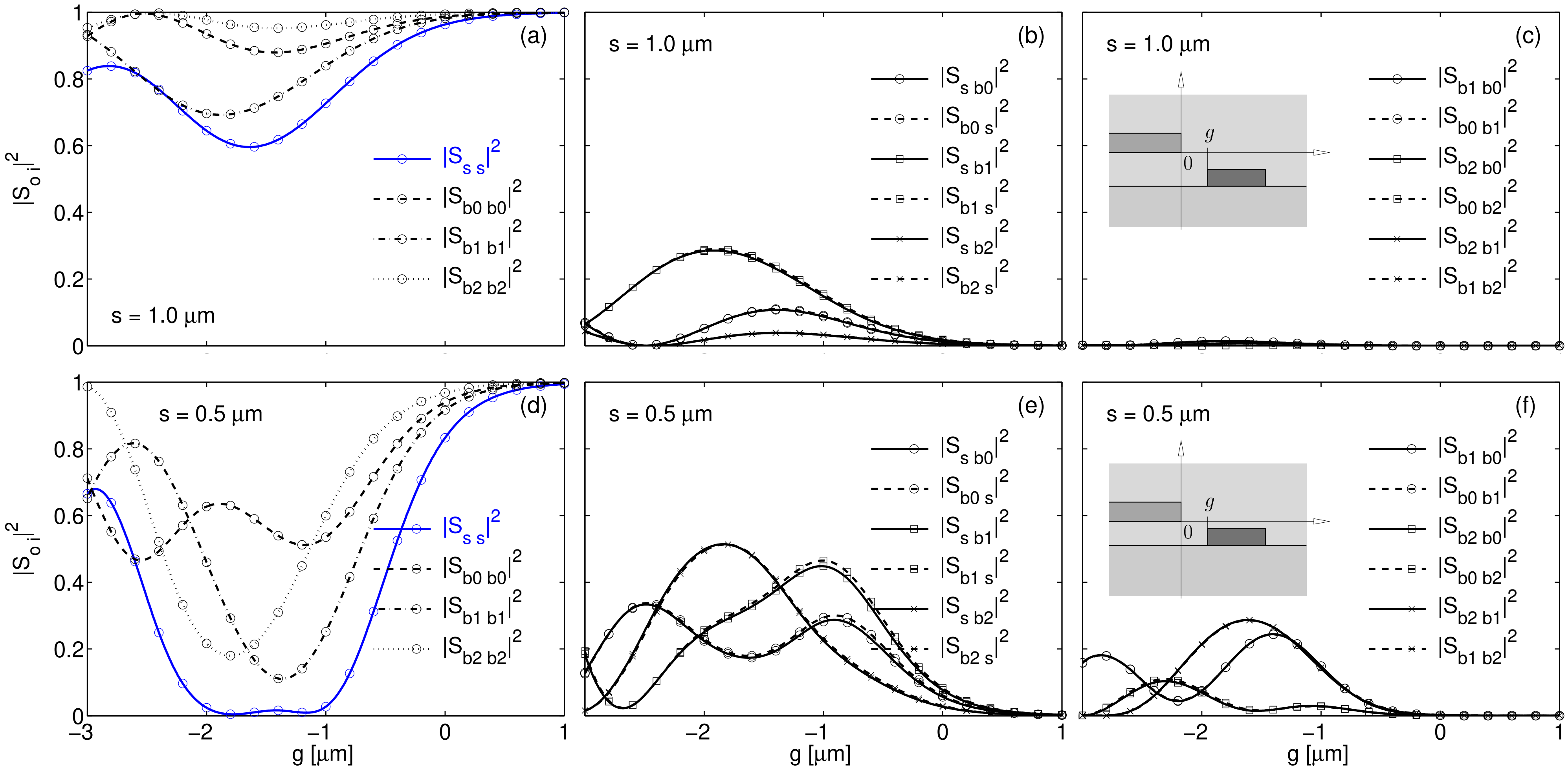
Bus waveguides:
one TE-like mode, s, $n_{\text{eff}} = 1.48229$.

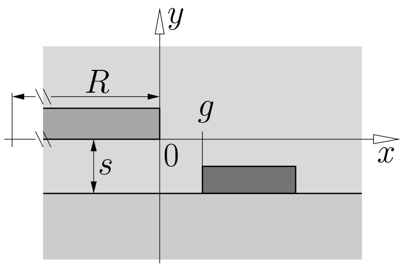
(Bend) mode analysis:
film mode matching (FMM) solver, semianalytical;
L. Prkna, M. Hubálek, J. Čtyroký,
J. Sel. Top. Quant. Electr. ***11****(1), 217-223 (2005).*

CMT

$$\begin{pmatrix} B_{\mathrm{s}} \\ b_{\mathrm{b0}} \\ b_{\mathrm{b1}} \\ b_{\mathrm{b2}} \end{pmatrix}_{z_{\mathrm{o}}} = \begin{pmatrix} S_{\mathrm{s\,s}} & S_{\mathrm{s\,b0}} & S_{\mathrm{s\,b1}} & S_{\mathrm{s\,b2}} \\ S_{\mathrm{b0\,s}} & S_{\mathrm{b0\,b0}} & S_{\mathrm{b0\,b1}} & S_{\mathrm{b0\,b2}} \\ S_{\mathrm{b1\,s}} & S_{\mathrm{b1\,b0}} & S_{\mathrm{b1\,b1}} & S_{\mathrm{b1\,b2}} \\ S_{\mathrm{b2\,s}} & S_{\mathrm{b2\,b0}} & S_{\mathrm{b2\,b1}} & S_{\mathrm{b2\,b2}} \end{pmatrix} \begin{pmatrix} A_{\mathrm{s}} \\ a_{\mathrm{b0}} \\ a_{\mathrm{b1}} \\ a_{\mathrm{b2}} \end{pmatrix}_{z_{\mathrm{i}}} .$$

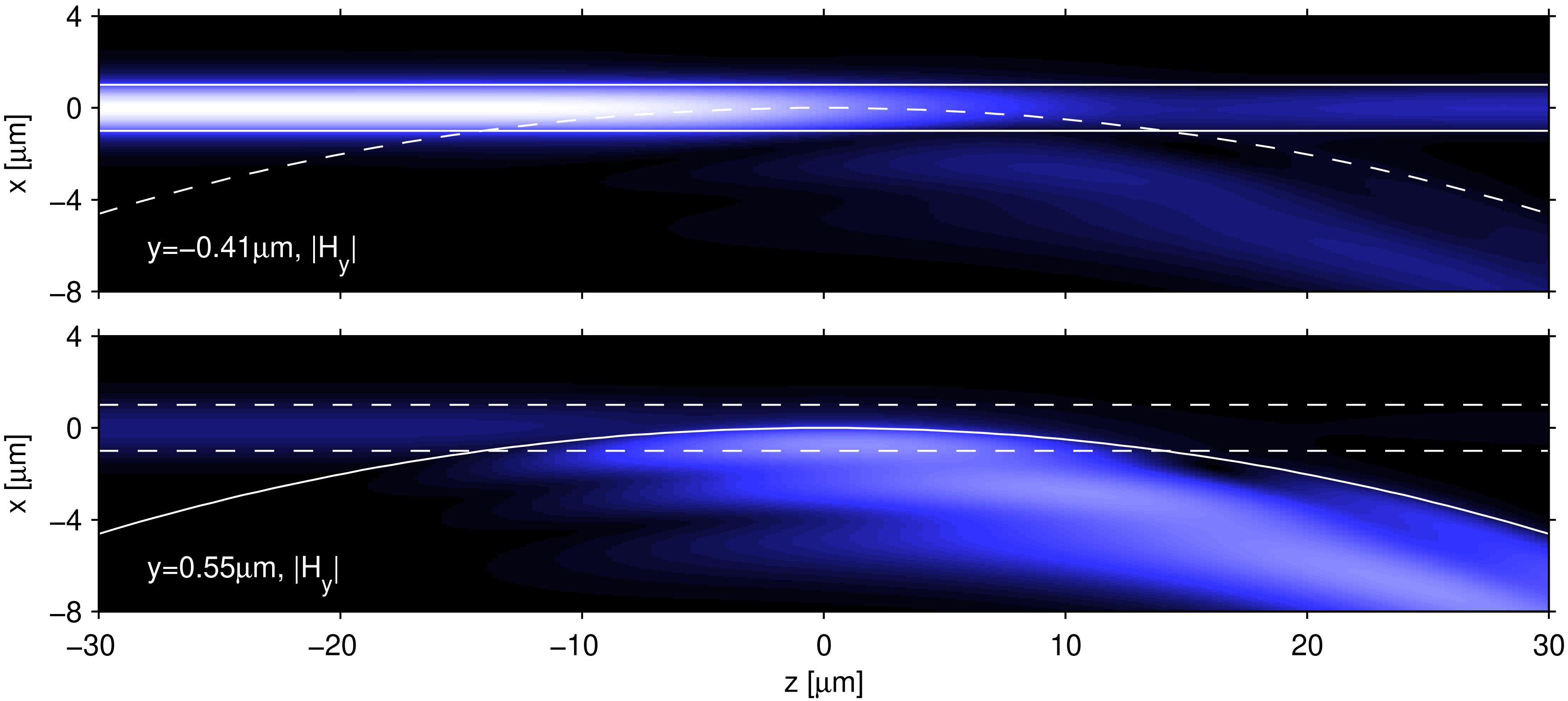
Vertical straight-disk-coupler, scattering matrices

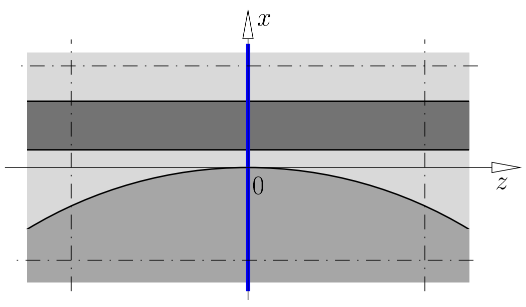


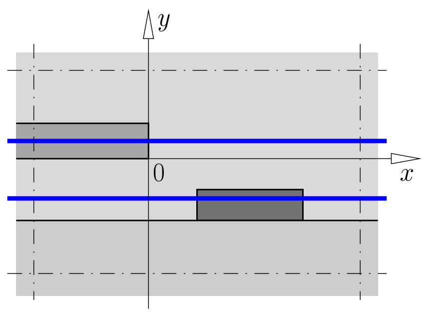


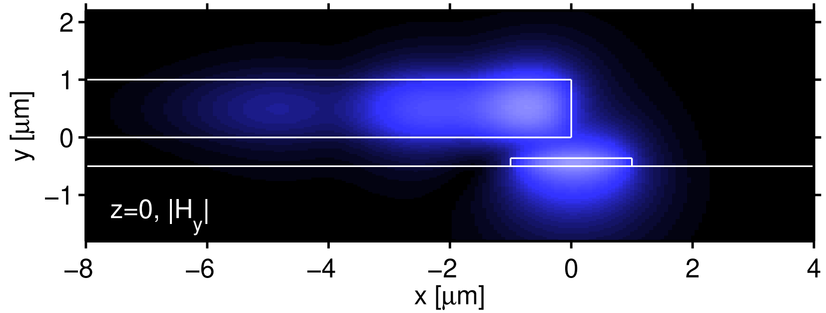
$$|S_{o\,i}|^2: \quad \text{power transfer} \quad \text{mode } i|_{z_\mathrm{i}} \;\rightarrow\; \text{mode } o|_{z_\mathrm{o}}\,.$$

Vertical straight-disk-coupler, field examples



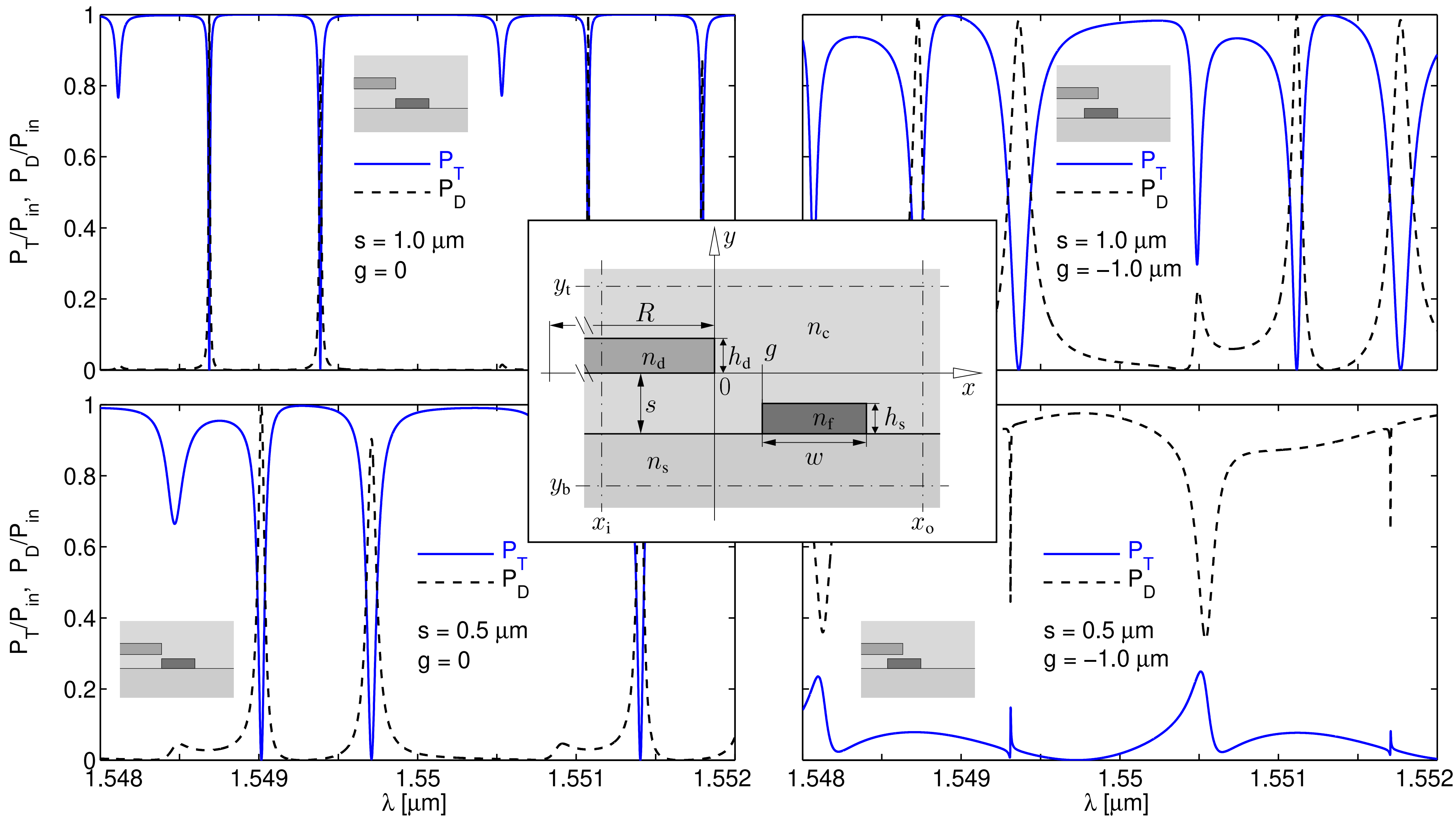




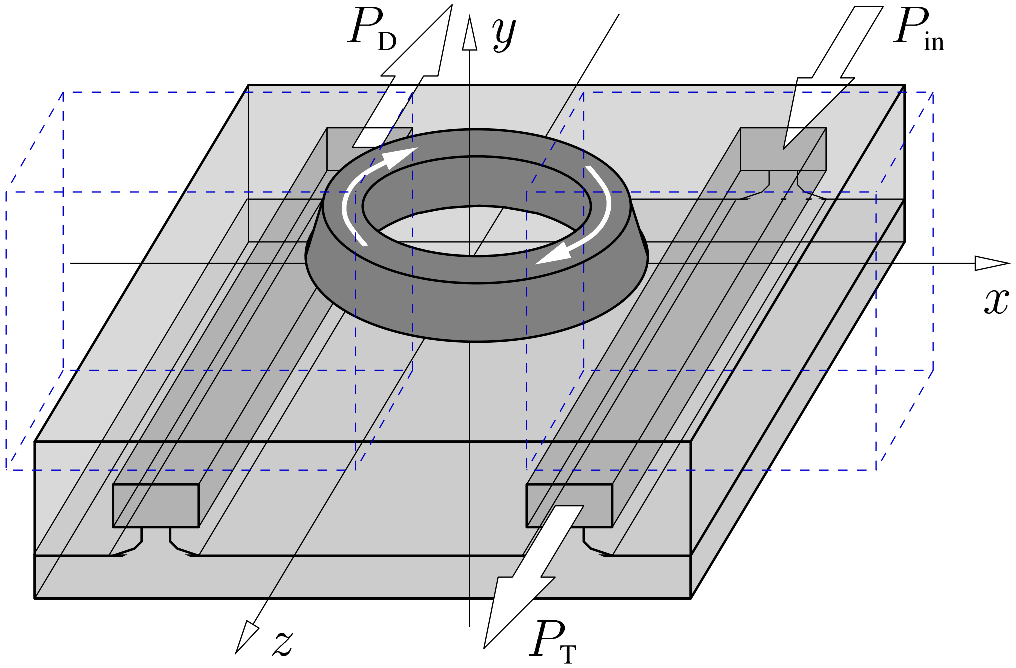


$s = 0.5\,\mu$m, $g = -1.0\,\mu$m; excitation in the bus waveguide.

Multimode microdisk-resonator, spectra



Resonator with hybrid ring cavity



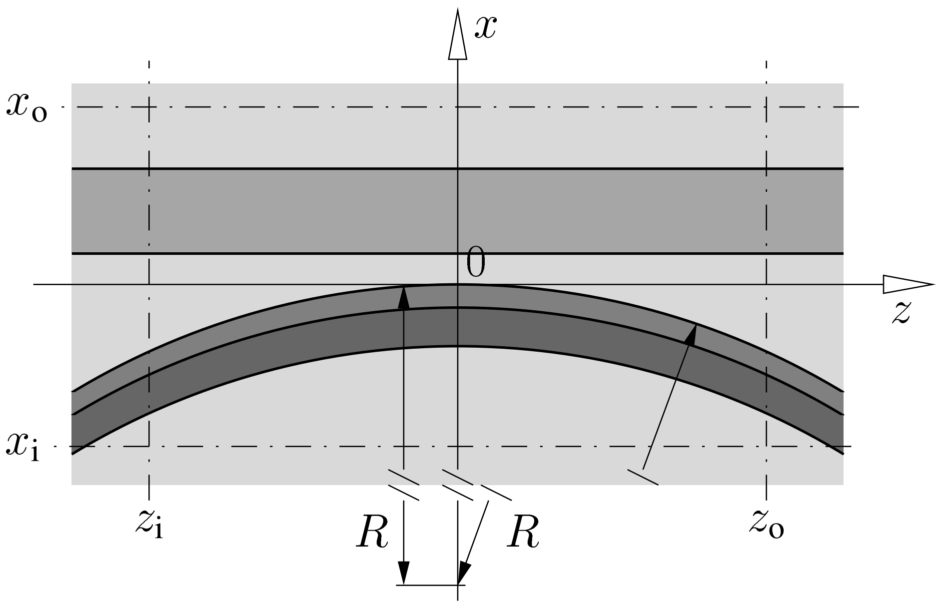
$n_f = 2.009$, $h_s = 0.27\,\mu$m, $w_s = 2.5\,\mu$m,
$n_s = 1.45$, $u = 0.9\,\mu$m

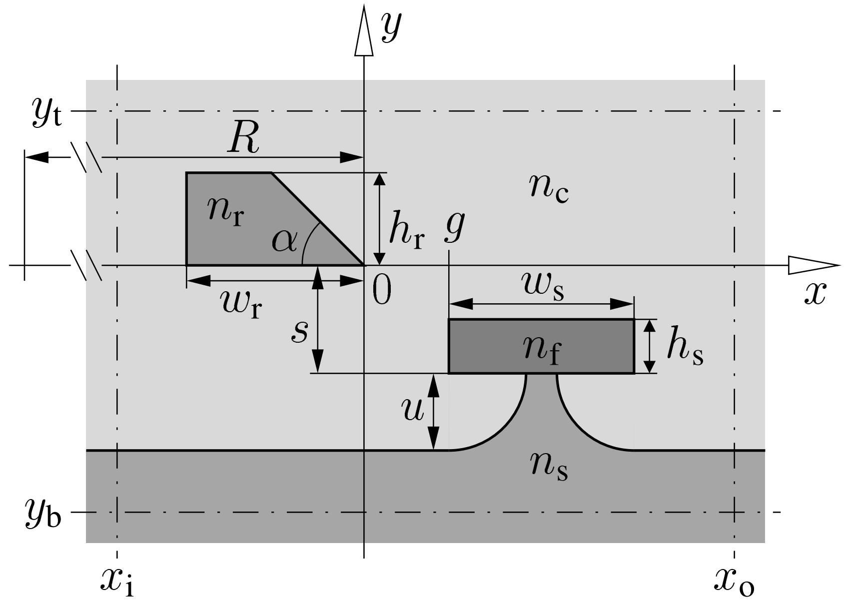
$n_r = 1.6275$, $w_r = 2.0\,\mu$m, $h_r = 1.0\,\mu$m,
$R = 100\,\mu$m, $\alpha = 48°$.

$s = 1.0\,\mu$m, $g = -2.25\,\mu$m, $n_c = 1.412$.

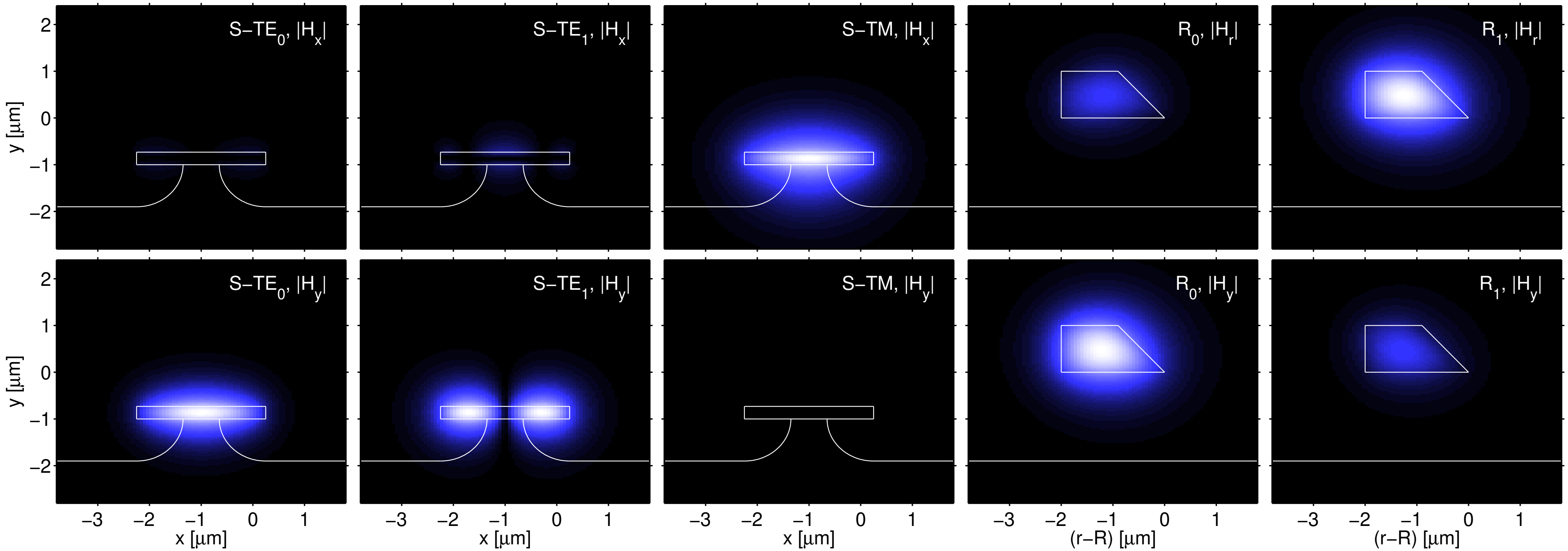
Target wavelength: $\lambda = 1.55\,\mu$m.

CMT computational window:
$[x_i, x_o] = [-12, 4]\,\mu$m,
$[y_b, y_t] = [-3.7, 4.4]\,\mu$m,
$[z_i, z_o] = [-35, 35]\,\mu$m.





Hybrid coupler, CMT basis fields & scattering matrix

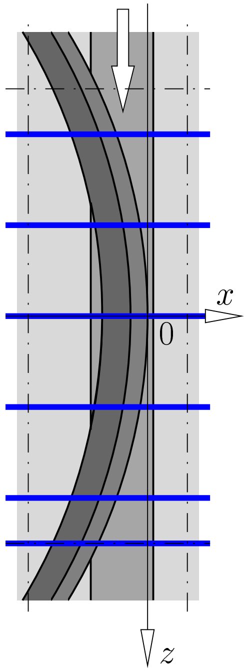


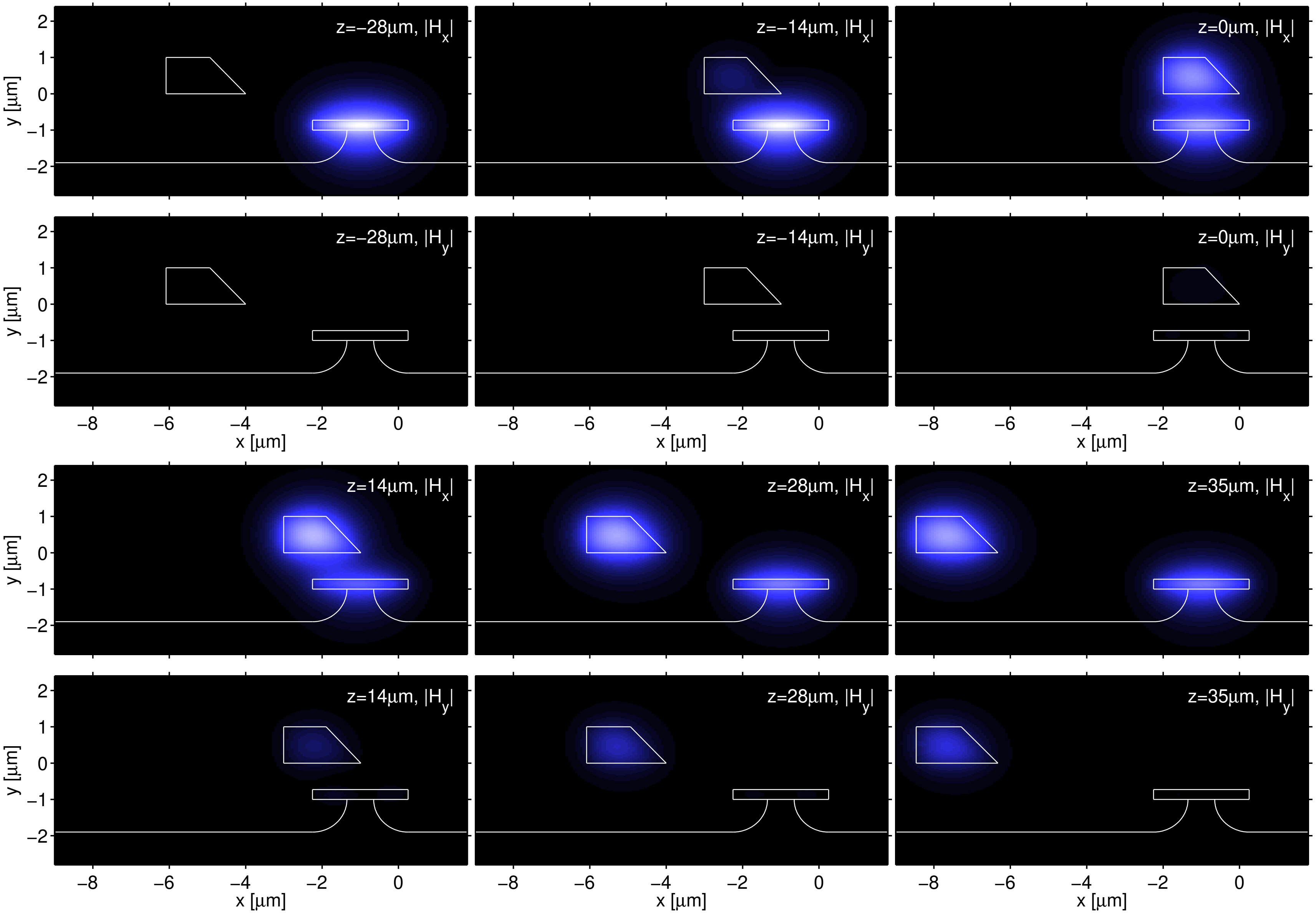
	$n_{\rm eff}$
S-TE$_0$	1.625326
S-TE$_1$	1.553733
S-TM	1.511020
R$_0$	$1.490975 - \mathrm{i}\, 2.7 \cdot 10^{-7}$
R$_1$	$1.483477 - \mathrm{i}\, 1.2 \cdot 10^{-7}$

CMT

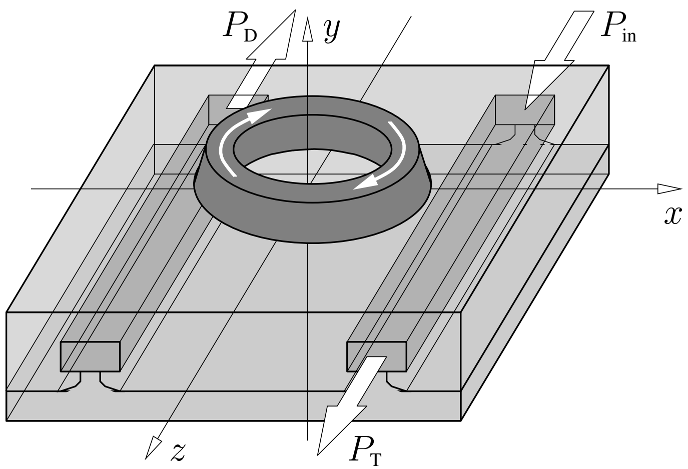
%	S-TE$_0$	S-TE$_1$	S-TM	R$_0$	R$_1$
S-TE$_0$	100.0	≈ 0	≈ 0	≈ 0	≈ 0
S-TE$_1$	≈ 0	97.8	≈ 0	1.9	0.1
S-TM	≈ 0	≈ 0	26.2	6.3	67.0
R$_0$	≈ 0	2.1	6.7	86.2	5.5
R$_1$	≈ 0	0.1	67.5	5.2	27.3

Hybrid coupler, CMT field example

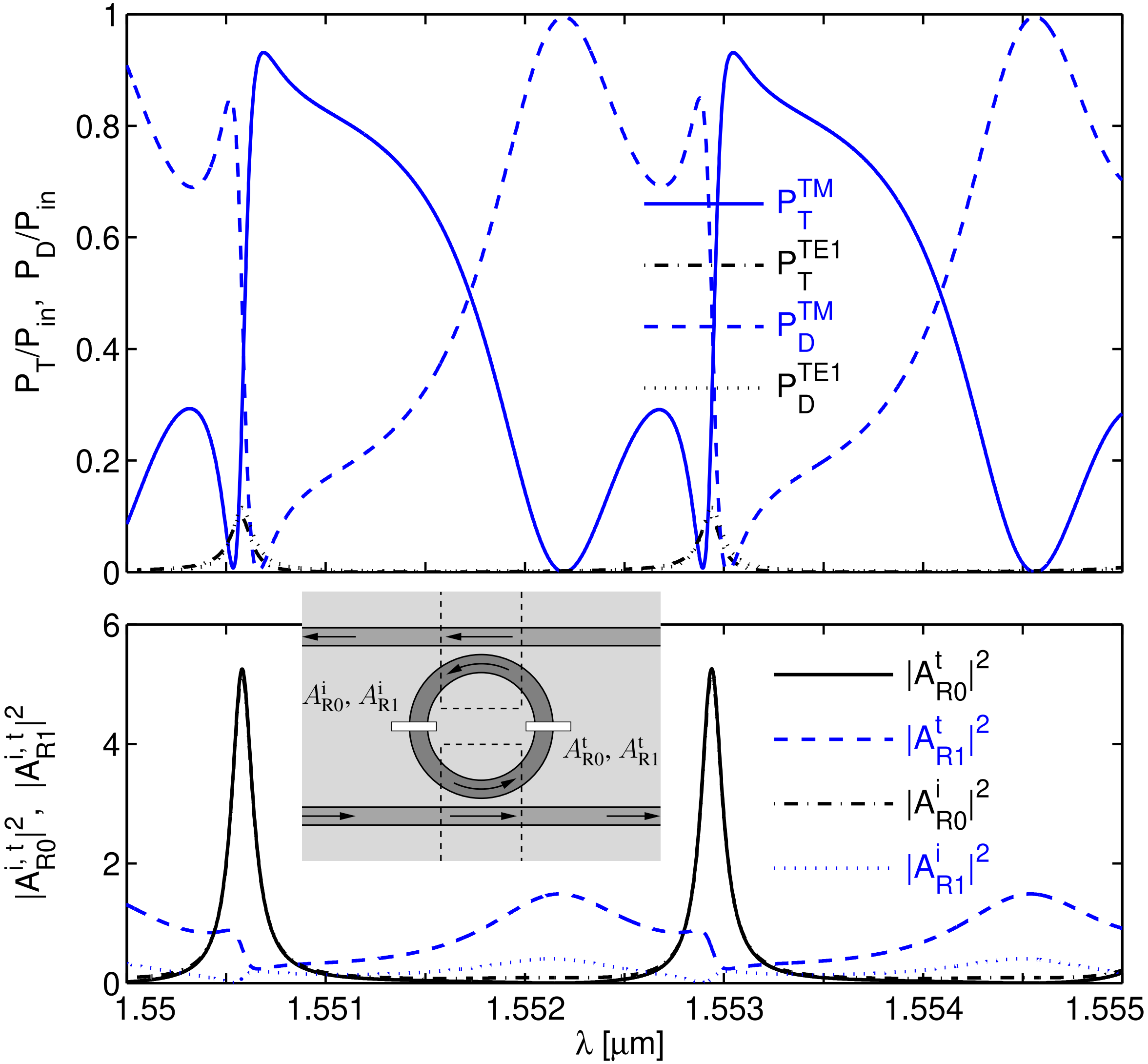




Resonator with hybrid ring cavity, spectrum



%	S-TE$_0$	S-TE$_1$	S-TM	R$_0$	R$_1$
S-TE$_0$	100.0	–	–	–	–
S-TE$_1$	–	97.8	–	1.9	0.1
S-TM	–	–	26.2	6.3	67.0
R$_0$	–	2.1	6.7	86.2	5.5
R$_1$	–	0.1	67.5	5.2	27.3



3-D Microresonator Simulator