Hybrid Coupled Mode Modelling in 3-D

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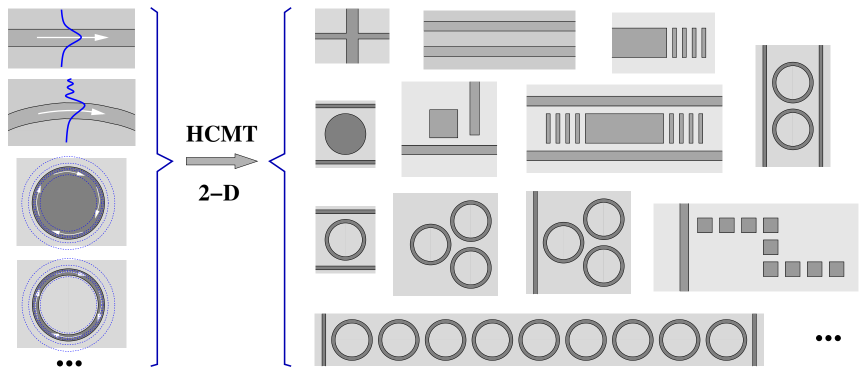
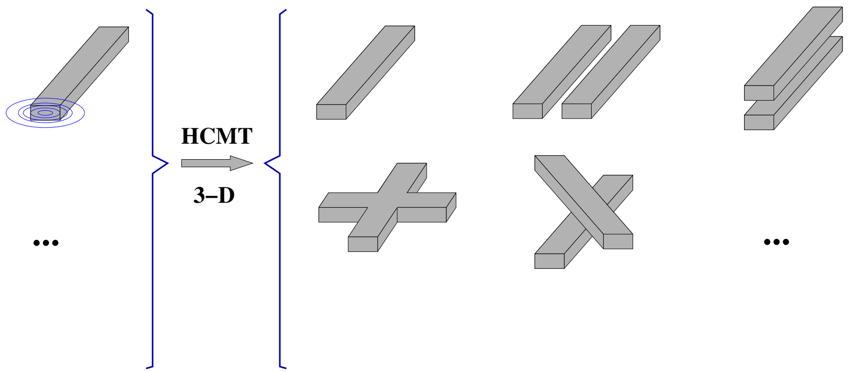
Wave interaction in photonic integrated circuits



Wave interaction in photonic integrated circuits



Hybrid Coupled Mode Modelling in 3-D

- Hybrid coupled mode theory (HCMT)
  - Field template
  - Amplitude discretization
  - Solution procedure
- Basis fields, 3-D
- Single straight channels
- Parallel waveguides
- Waveguide crossings

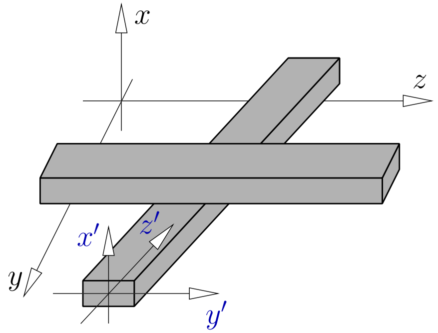
Frequency domain,
$\sim \exp(\mathrm{i}\omega t)$,

$$\left.\begin{array}{r} \boldsymbol{\nabla} \times \boldsymbol{H} - \mathrm{i}\omega\epsilon_0\epsilon \boldsymbol{E} = 0, \\ -\boldsymbol{\nabla} \times \boldsymbol{E} - \mathrm{i}\omega\mu_0 \boldsymbol{H} = 0, \end{array}\right\}$$

$\omega = k\mathrm{c} = 2\pi\mathrm{c}/\lambda$ given,

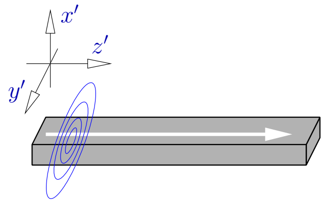
$\epsilon = n^2, \quad n(x, y, z).$

A waveguide crossing



... local coordinates $x', y', z',$ per channel, per mode.

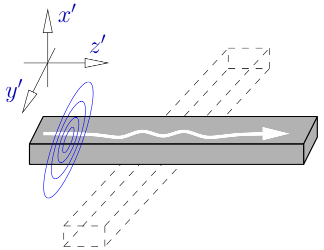
Field template, local



Guided mode with profile $(\tilde{\boldsymbol{E}}, \tilde{\boldsymbol{H}})$,
propagation constant $\beta = k\, n_{\mathrm{eff}}$:

$$\begin{pmatrix}\boldsymbol{E}\\ \boldsymbol{H}\end{pmatrix}(x', y', z') = \begin{pmatrix}\tilde{\boldsymbol{E}}\\ \tilde{\boldsymbol{H}}\end{pmatrix}(x', y')\,\mathrm{e}^{-\mathrm{i}\beta z'}$$

Field template, local

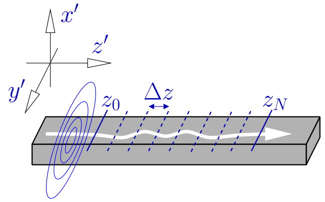


Guided mode with profile $(\tilde{\boldsymbol{E}}, \tilde{\boldsymbol{H}})$,
propagation constant $\beta = k\, n_{\mathrm{eff}}$:

$$\begin{pmatrix}\boldsymbol{E}\\ \boldsymbol{H}\end{pmatrix}(x', y', z') \approx a(z') \begin{pmatrix}\tilde{\boldsymbol{E}}\\ \tilde{\boldsymbol{H}}\end{pmatrix}(x', y')\,\mathrm{e}^{-\mathrm{i}\beta z'},$$

$$a = \,?$$

Field template, local



Guided mode with profile $(\tilde{\boldsymbol{E}}, \tilde{\boldsymbol{H}})$,
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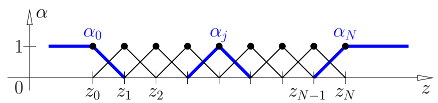
$$\begin{pmatrix}\boldsymbol{E}\\ \boldsymbol{H}\end{pmatrix}(x', y', z') \approx a(z') \begin{pmatrix}\tilde{\boldsymbol{E}}\\ \tilde{\boldsymbol{H}}\end{pmatrix}(x', y')\,\mathrm{e}^{-\mathrm{i}\beta z'},$$

$$a = \,?$$

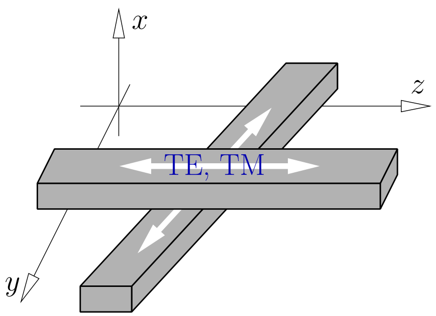
$$a(z') = \sum_{j=0}^{N} a_j\, \alpha_j(z'),$$



$$\begin{pmatrix}\boldsymbol{E}\\ \boldsymbol{H}\end{pmatrix}(x', y', z') = \sum_j a_j \left(\alpha_j(z') \begin{pmatrix}\tilde{\boldsymbol{E}}\\ \tilde{\boldsymbol{H}}\end{pmatrix}(x', y')\,\mathrm{e}^{-\mathrm{i}\beta z'}\right) =: \sum_j a_j \begin{pmatrix}\boldsymbol{E}_j\\ \boldsymbol{H}_j\end{pmatrix}(x', y', z'),$$

$$a_j = \,?$$

Field template, global



- Local ansatz for all channels, modes,
- $(x', y', z') \rightsquigarrow (x, y, z)$,
- $\sum$ (local contributions)

$$\hookrightarrow \quad \begin{pmatrix}\boldsymbol{E}\\ \boldsymbol{H}\end{pmatrix}(x,y,z) = \sum_k a_k \begin{pmatrix}\boldsymbol{E}_k\\ \boldsymbol{H}_k\end{pmatrix}(x,y,z),$$

$$a_k = ?$$

Galerkin procedure

$$\begin{aligned} \boldsymbol{\nabla}\times\boldsymbol{H} - \mathrm{i}\omega\epsilon_0\epsilon\boldsymbol{E} &= 0 \\ -\boldsymbol{\nabla}\times\boldsymbol{E} - \mathrm{i}\omega\mu_0\boldsymbol{H} &= 0 \end{aligned} \quad \Bigg| \qquad \cdot\begin{pmatrix}\boldsymbol{F}\\ \boldsymbol{G}\end{pmatrix}^{*}, \qquad \iiint$$

$$\leftrightsquigarrow \quad \iiint \mathcal{K}(\boldsymbol{F},\boldsymbol{G};\boldsymbol{E},\boldsymbol{H})\,\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z = 0 \quad \text{for all } \boldsymbol{F},\ \boldsymbol{G},$$

where

$$\mathcal{K}(\boldsymbol{F},\boldsymbol{G};\boldsymbol{E},\boldsymbol{H}) = \boldsymbol{F}^*\cdot(\boldsymbol{\nabla}\times\boldsymbol{H}) - \boldsymbol{G}^*\cdot(\boldsymbol{\nabla}\times\boldsymbol{E}) - \mathrm{i}\omega\epsilon_0\epsilon\boldsymbol{F}^*\cdot\boldsymbol{E} - \mathrm{i}\omega\mu_0\boldsymbol{G}^*\cdot\boldsymbol{H}\,.$$

Galerkin procedure, continued

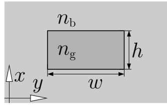
- Insert $\begin{pmatrix}\boldsymbol{E}\\ \boldsymbol{H}\end{pmatrix} = \sum_k a_k \begin{pmatrix}\boldsymbol{E}_k\\ \boldsymbol{H}_k\end{pmatrix}$,
- select $\{\mathrm{u}\}$: indices of unknown coefficients,
  $\{\mathrm{g}\}$: given values related to prescribed influx,
- require $\iiint \mathcal{K}(\boldsymbol{E}_l,\boldsymbol{H}_l;\boldsymbol{E},\boldsymbol{H})\,\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z = 0$ for $l\in\{\mathrm{u}\}$,
- compute $K_{lk} = \iiint \mathcal{K}(\boldsymbol{E}_l,\boldsymbol{H}_l;\boldsymbol{E}_k,\boldsymbol{H}_k)\,\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,.$

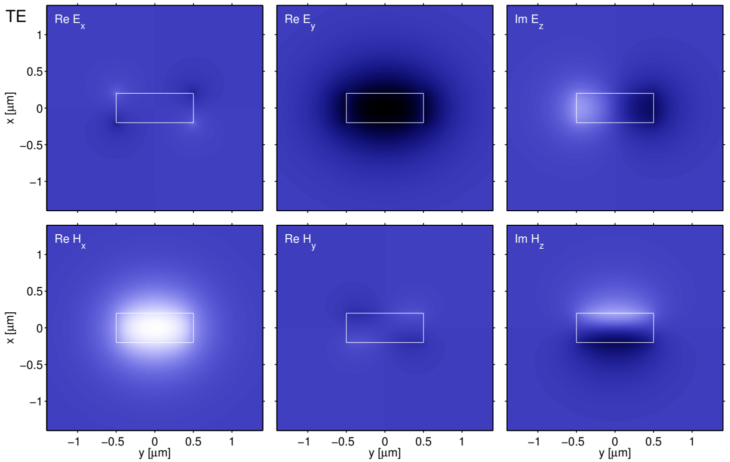
$$\sum_{k\in\{\mathrm{u},\mathrm{g}\}} K_{lk}a_k = 0\,,\ l\in\{\mathrm{u}\}\,, \qquad (\mathsf{K}_{\mathrm{u\,u}}\ \mathsf{K}_{\mathrm{u\,g}})\begin{pmatrix}\boldsymbol{a}_{\mathrm{u}}\\ \boldsymbol{a}_{\mathrm{g}}\end{pmatrix} = 0\,, \qquad \text{or} \qquad \mathsf{K}_{\mathrm{u\,u}}\boldsymbol{a}_{\mathrm{u}} = -\mathsf{K}_{\mathrm{u\,g}}\boldsymbol{a}_{\mathrm{g}}\,.$$

Further issues

… plenty.

Basis modes



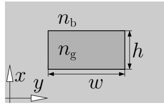


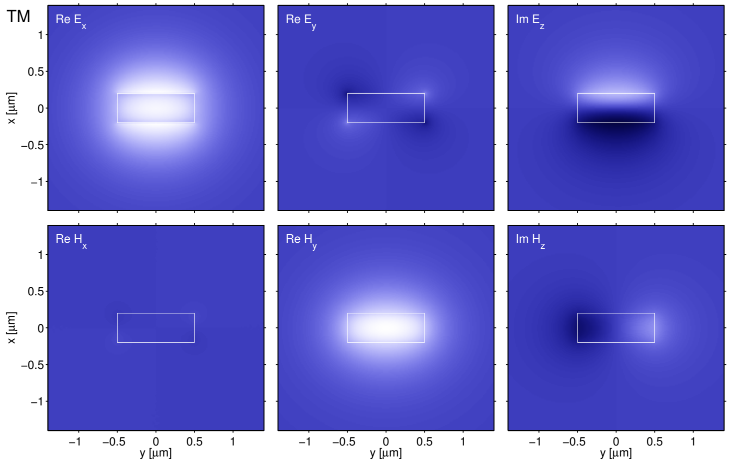
$\lambda = 1.55$ μm,
$n_b = 1.45$,
$n_g = 1.99$,
$w = 1.0$ μm,
$h = 0.4$ μm;

$x \in [-2, 2]$ μm,
$y \in [-2, 2]$ μm;

$n_{\mathrm{eff,TE}} = 1.63554$
[JCMwave].

Basis modes





$\lambda = 1.55$ μm,
$n_b = 1.45$,
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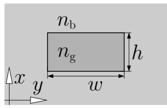
$w = 1.0$ μm,
$h = 0.4$ μm;

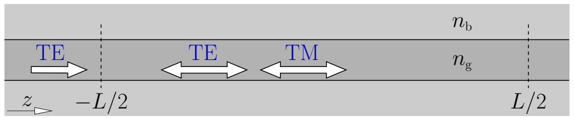
$x \in [-2, 2]$ μm,
$y \in [-2, 2]$ μm;

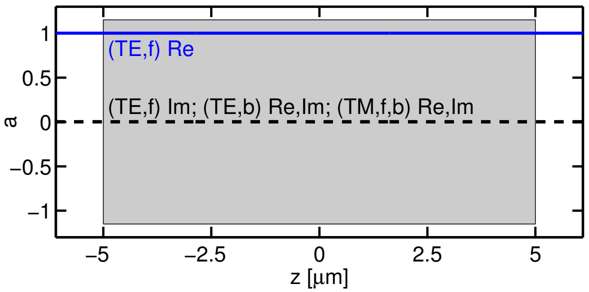
$n_{\mathrm{eff,TM}} = 1.56809$
[JCMwave].

A single channel

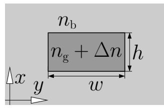


$z \in [-5, 5]$ μm,
$\Delta z = 0.5$ μm.

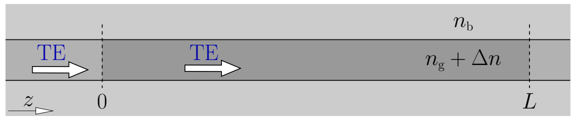




A single channel

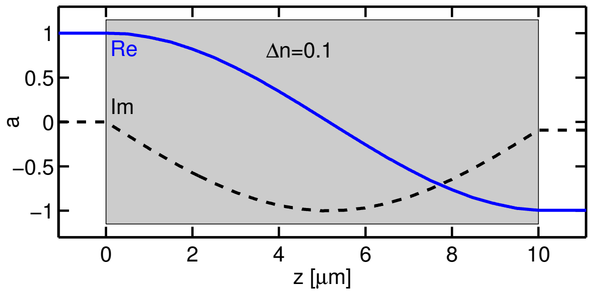


$z \in [0, 10]$ μm,
$\Delta z = 0.5$ μm.

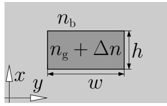


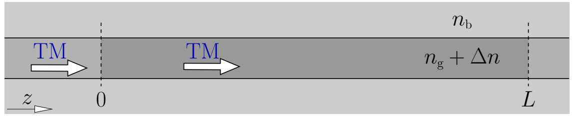
$$\mathrm{e}^{-\mathrm{i}kn^{\mathrm{p}}_{\mathrm{eff}}z} = a(z)\,\mathrm{e}^{-\mathrm{i}kn^{0}_{\mathrm{eff}}z},$$
$$a(z) \rightsquigarrow \Delta n_{\mathrm{eff}} = n^{\mathrm{p}}_{\mathrm{eff}} - n^{0}_{\mathrm{eff}}.$$

TE, $\Delta n = 0.1$	Δn_{eff}
HCMT	0.075
JCMwave	0.078



A single channel

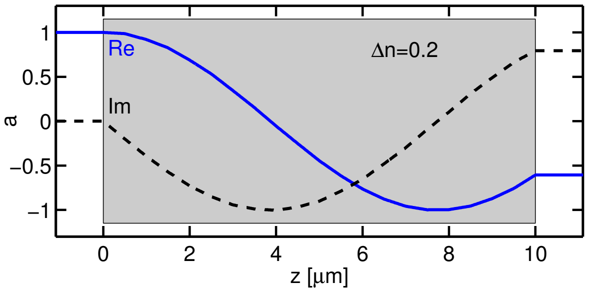




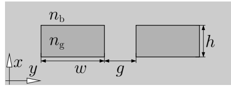
$z \in [0, 10]$ µm,
$\Delta z = 0.5$ µm.

$$\mathrm{e}^{-\mathrm{i}kn_{\mathrm{eff}}^{\mathrm{p}}z} = a(z)\ \mathrm{e}^{-\mathrm{i}kn_{\mathrm{eff}}^{0}z},$$
$$a(z) \rightsquigarrow \Delta n_{\mathrm{eff}} = n_{\mathrm{eff}}^{\mathrm{p}} - n_{\mathrm{eff}}^{0}.$$

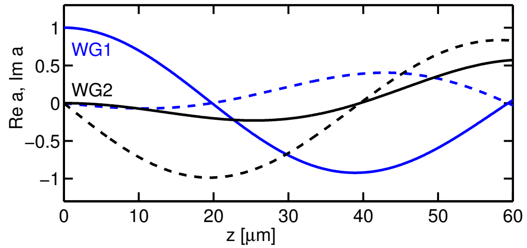
TM, $\Delta n = 0.2$	Δn_{eff}
HCMT	0.100
JCMwave	0.110

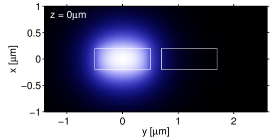


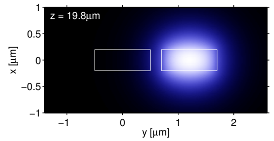
Parallel channels, horizontal coupling

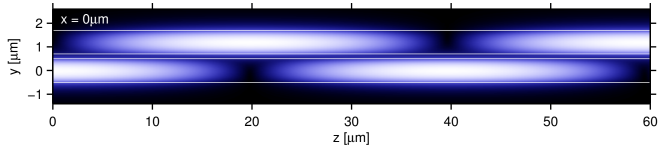


TE, $\lambda = 1.55$ µm, $n_b = 1.45$, $n_g = 1.99$,
$w = 1.0$ µm, $h = 0.4$ µm, $g = 0.2$ µm.

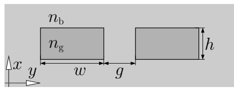




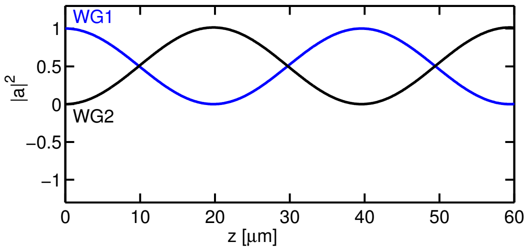


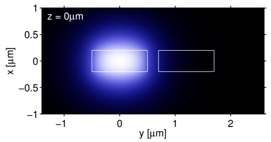


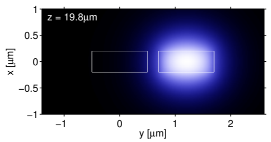
Parallel channels, horizontal coupling

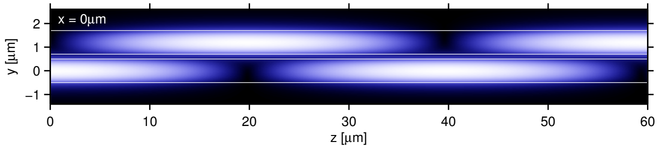


TE, $\lambda = 1.55$ µm, $n_b = 1.45$, $n_g = 1.99$,
$w = 1.0$ µm, $h = 0.4$ µm, $g = 0.2$ µm.

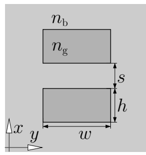




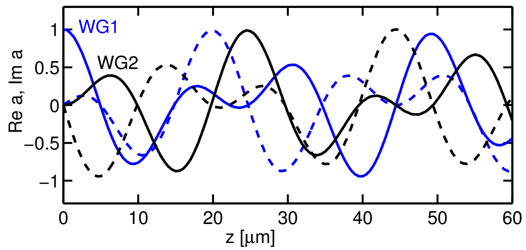


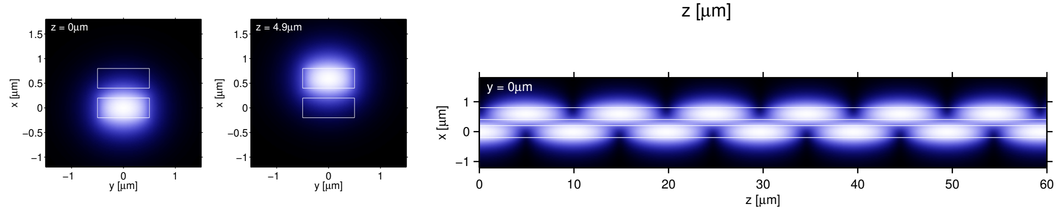


Parallel channels, vertical coupling

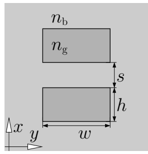


TE,
$\lambda = 1.55$ µm,
$n_b = 1.45$,
$n_g = 1.99$,
$w = 1.0$ µm,
$h = 0.4$ µm,
$s = 0.2$ µm.

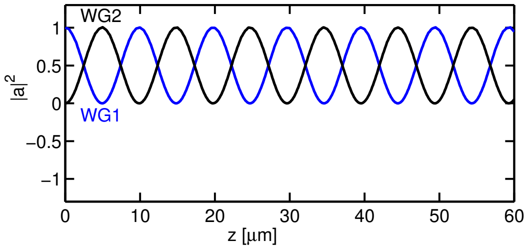


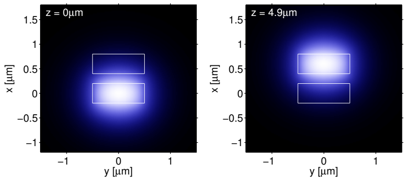


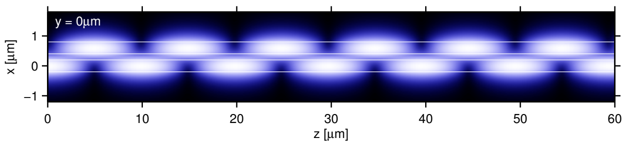
Parallel channels, vertical coupling



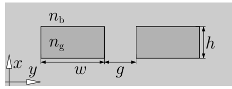
TE,
$\lambda = 1.55\ \mu m$,
$n_b = 1.45$,
$n_g = 1.99$,
$w = 1.0\ \mu m$,
$h = 0.4\ \mu m$,
$s = 0.2\ \mu m$.



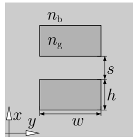




Parallel channels, coupling length



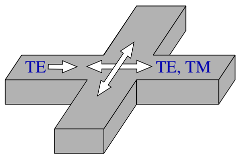
$L_c/\ \mu m$	$g = 0.2\ \mu m$		$g = 0.3\ \mu m$		$g = 0.4\ \mu m$	
	TE	TM	TE	TM	TE	TM
HCMT	19.8	16.8	28.2	22.8	39.5	30.4
JCMwave	19.5	16.9	28.2	22.5	40.4	29.8

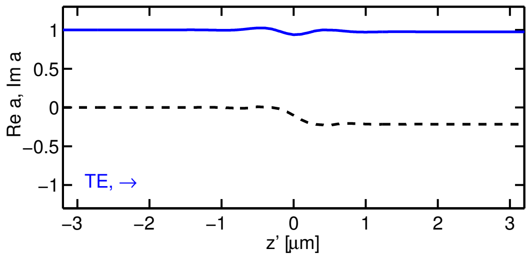


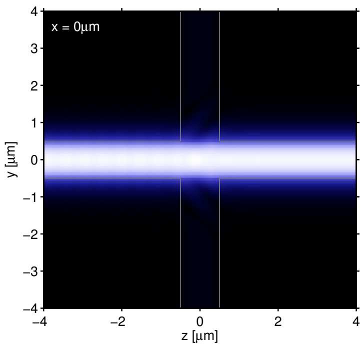
$L_c/\ \mu m$	$s = 0.2\ \mu m$		$s = 0.4\ \mu m$		$s = 0.6\ \mu m$		$s = 0.8\ \mu m$	
	TE	TM	TE	TM	TE	TM	TE	TM
HCMT	4.9	4.9	10.5	8.2	21.4	14.4	42.7	25.2
JCMwave	5.1	5.0	10.6	8.4	21.4	14.8	42.5	25.8

HCMT: $a(z) \rightsquigarrow L_c$,
JCMwave: $L_c = \pi / |\beta_s - \beta_a|$.

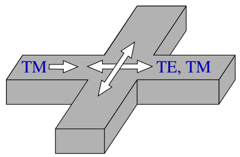
Waveguide crossing, perpendicular

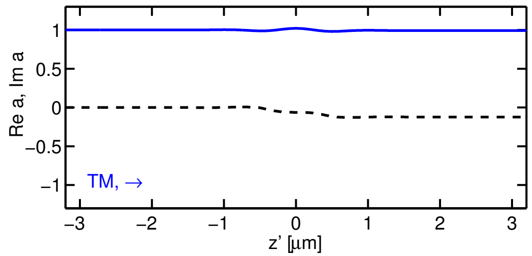


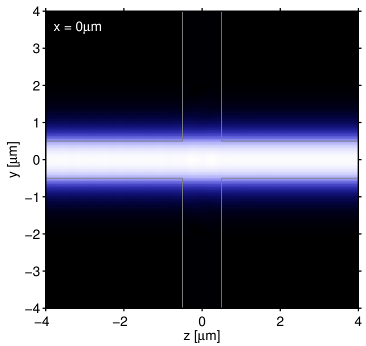




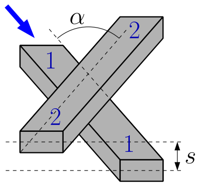
Waveguide crossing, perpendicular



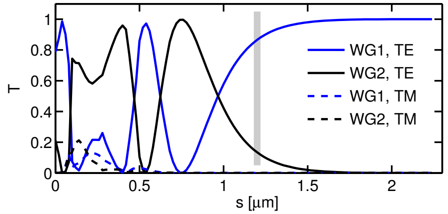


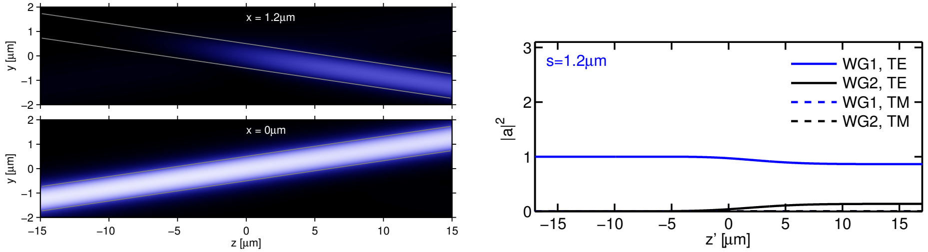


Waveguide crossing, oblique

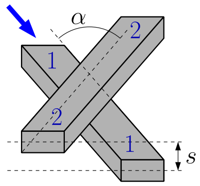


$\alpha = 9.44°$,
TE input,
$s = 1.2$ µm.

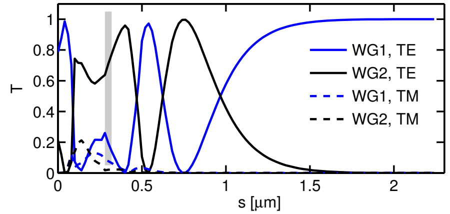


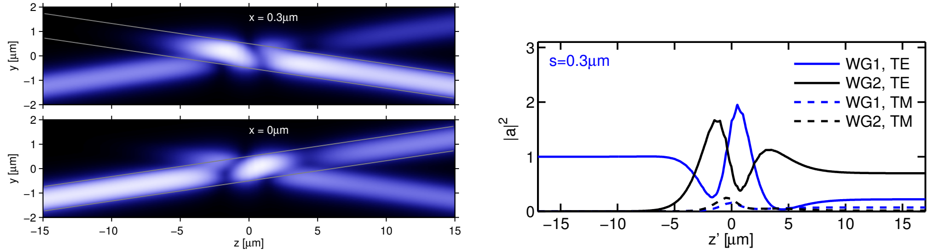


Waveguide crossing, oblique

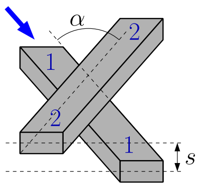


$\alpha = 9.44°$,
TE input,
$s = 0.3$ µm.

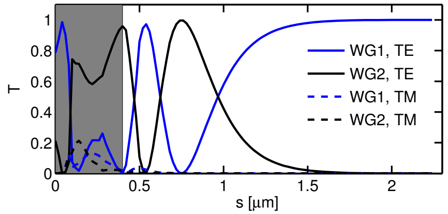


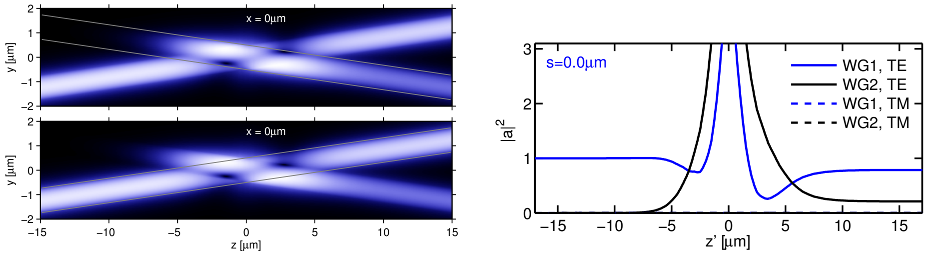


Waveguide crossing, oblique

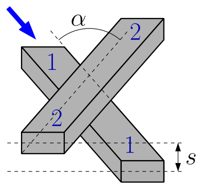


$\alpha = 9.44°$,
TE input,
$s = 0.0$ µm.

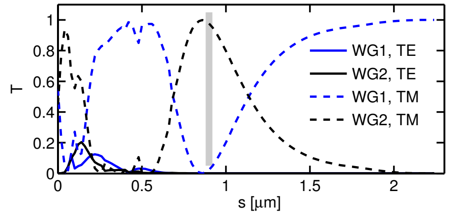


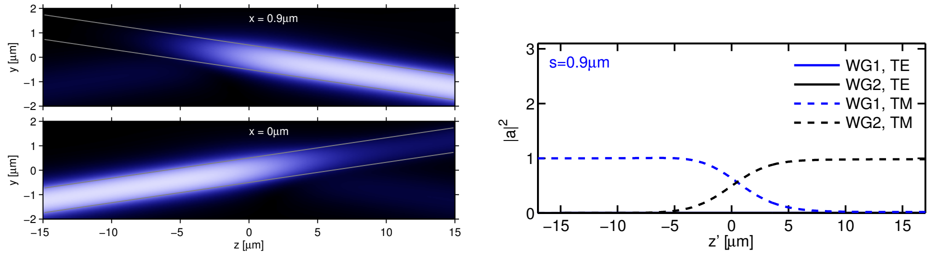


Waveguide crossing, oblique

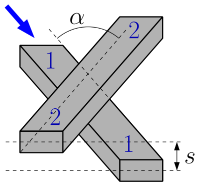


$\alpha = 9.44°$,
TM input,
$s = 0.9$ µm.

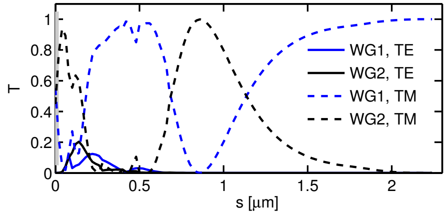


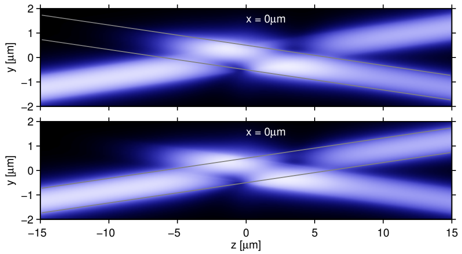


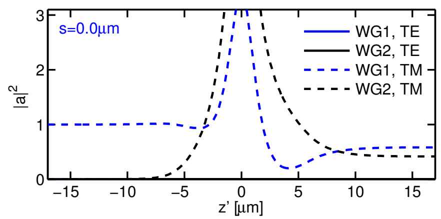
Waveguide crossing, oblique



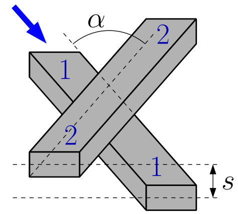
$\alpha = 9.44°$,
TM input,
$s = 0.0\ \mu m$.



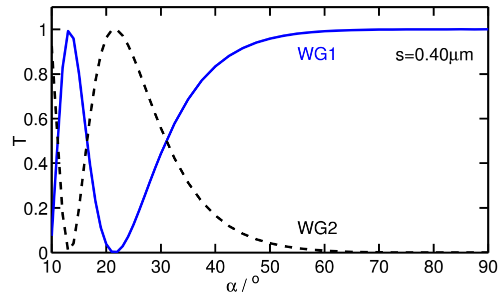




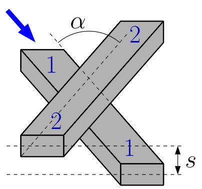
Waveguide crossing, oblique



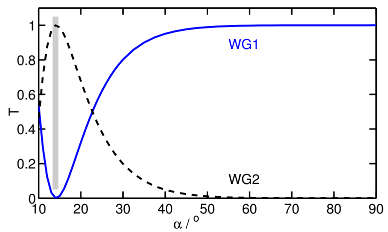
TE input.

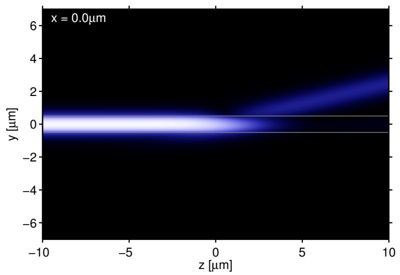


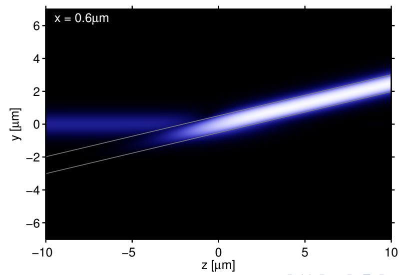
Waveguide crossing, oblique



TE,
$s = 0.6\ \mu m$,
$\alpha = 14°$.







Concluding remarks

Hybrid Coupled Mode Theory:

- an ab-initio, quantitative, quite general CMT variant, very close to common ways of reasoning in integrated optics,
- alternatively: a numerical (FEM) approach with highly specialized base functions,
- extension to 3-D possible, numerical basis fields, still moderate effort (in progress),
- benchmarking required (in progress).