Oblique Semi-Guided Waves:
2-D Integrated Photonics with Negative Effective Permittivity

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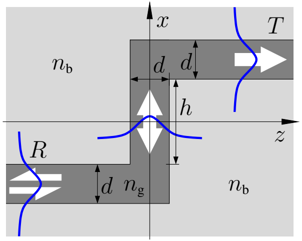
A dielectric step



$n_g = 3.4$, $n_b = 1.45$,
$d = 0.25$ µm, $h = 2.15$ µm,
$\lambda = 1.55$ µm, in: TE_0.

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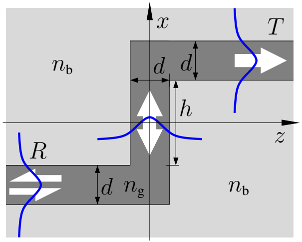

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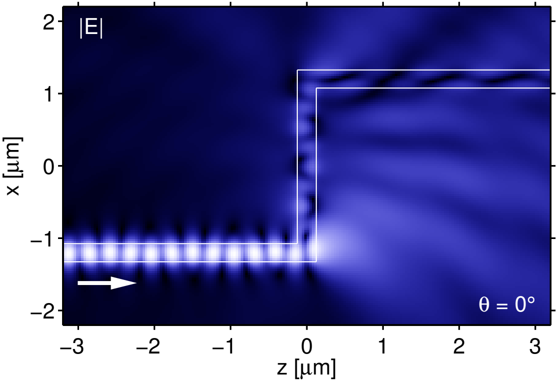
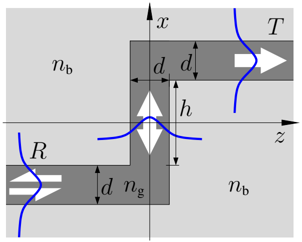
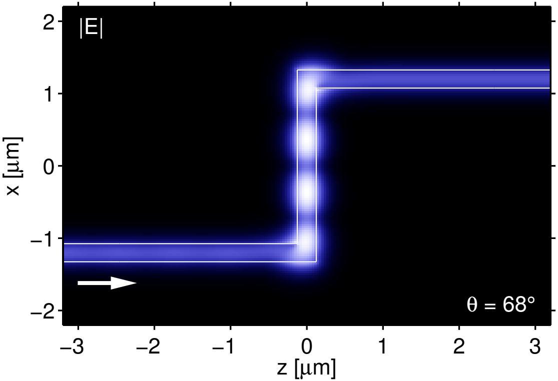


$T_{TE} = 0.01$, $R_{TE} = 0.12$, $T_{TM} = 0$, $R_{TM} = 0$.

A dielectric step

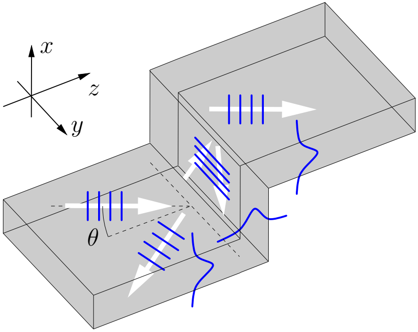


$n_g = 3.4,\ n_b = 1.45,$
$d = 0.25\ \mu m,\ h = 2.15\ \mu m,$
$\lambda = 1.55\ \mu m,$ in: TE_0.

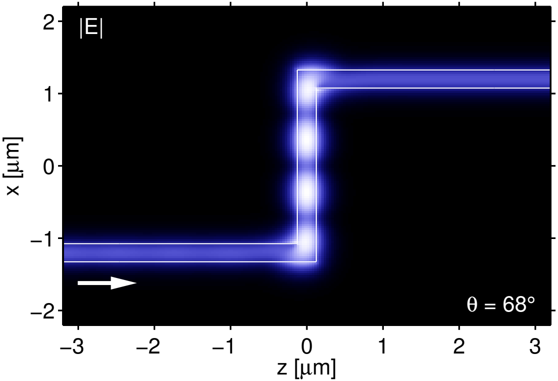


$T_{TE} > 0.99,\ R_{TE} < 0.01,\ T_{TM} = 0,\ R_{TM} = 0.$

A dielectric step



Oblique incidence !

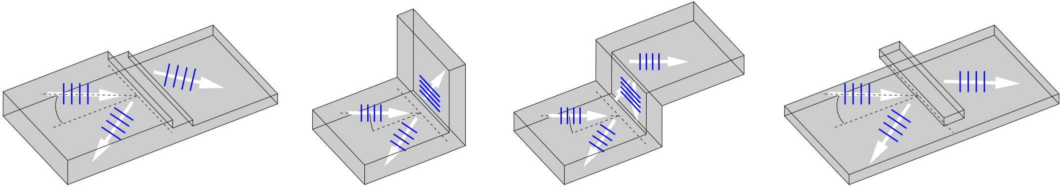


$T_{\text{TE}} > 0.99,\ R_{\text{TE}} < 0.01,\ T_{\text{TM}} = 0,\ R_{\text{TM}} = 0.$

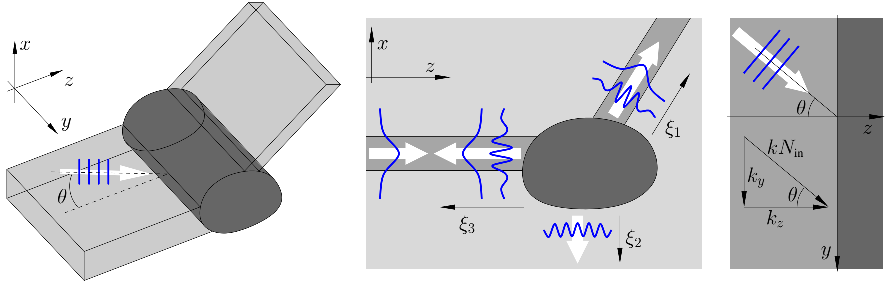
Oblique semi-guided waves

Overview

- Snell's law, critical angles
- Waveguide junctions
- 90°-corners, step configurations
- Strip resonator
- Semi-guided beams



Snell's law



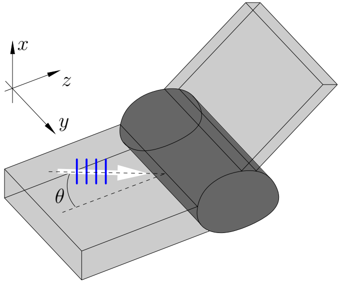
$$\sim \ \mathrm{e}^{\mathrm{i}\omega t}, \ \omega = kc = 2\pi c/\lambda$$

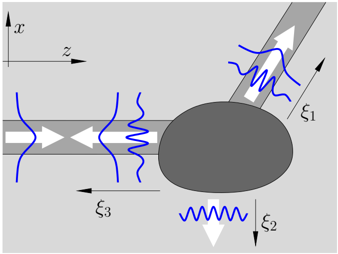
- Incoming slab mode $\{N_{\text{in}}; \mathbf{\Psi}_{\text{in}}\}$, $(\boldsymbol{E}, \boldsymbol{H}) \sim \mathbf{\Psi}_{\text{in}}(x)\,\mathrm{e}^{-\mathrm{i}\,(k_y y + k_z z)}$,

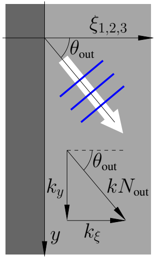
  incidence angle θ, $k^2 N_{\text{in}}^2 = k_y^2 + k_z^2$, $k_y = kN_{\text{in}} \sin\theta$.

- y-homogeneous problem: $(\boldsymbol{E}, \boldsymbol{H}) \sim \mathrm{e}^{-\mathrm{i}k_y y}$ everywhere.

Snell's law



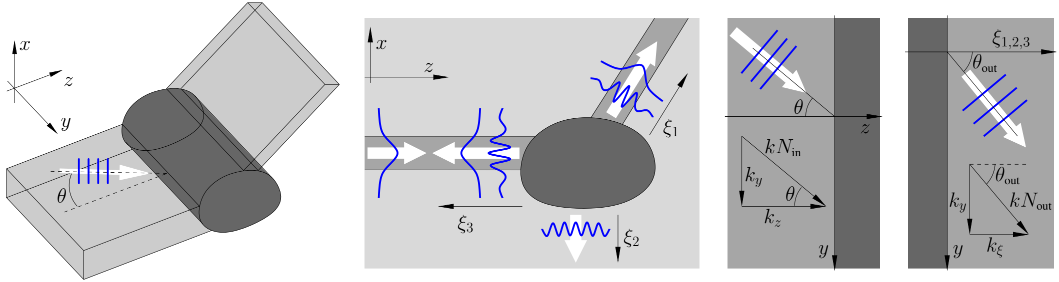




- Outgoing wave $\{N_{\text{out}}; \boldsymbol{\Psi}_{\text{out}}\}$, $\quad (\boldsymbol{E}, \boldsymbol{H}) \sim \boldsymbol{\Psi}_{\text{out}}(\,.\,)\,\mathrm{e}^{-\mathrm{i}(k_y y + k_\xi \xi)}$,

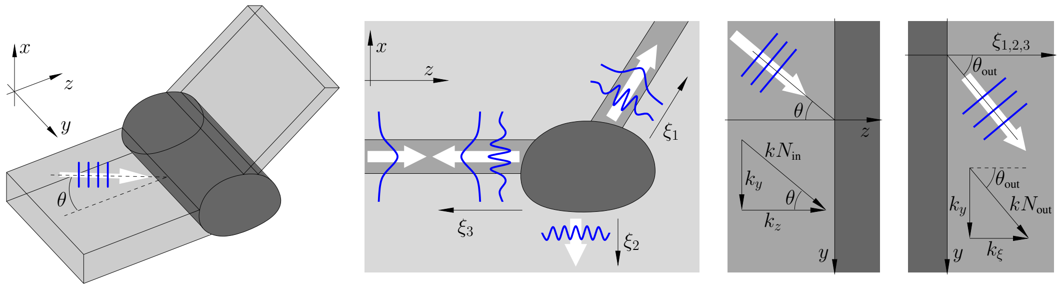
$$k^2 N_{\text{out}}^2 = k_y^2 + k_\xi^2, \quad k_y = kN_{\text{in}} \sin\theta.$$

Snell's law



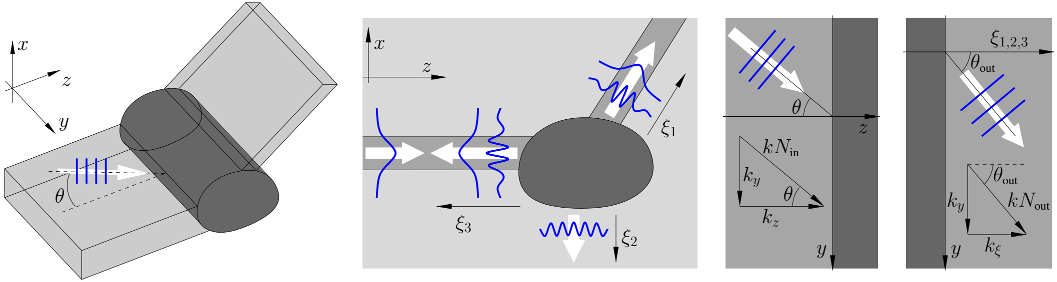
- Outgoing wave $\{N_{\text{out}}; \mathbf{\Psi}_{\text{out}}\}$, $(\boldsymbol{E}, \boldsymbol{H}) \sim \mathbf{\Psi}_{\text{out}}(\,.\,)\, \mathrm{e}^{-\mathrm{i}(k_y y + k_\xi \xi)}$,
$$k^2 N_{\text{out}}^2 = k_y^2 + k_\xi^2, \quad k_y = kN_{\text{in}} \sin\theta.$$
- $k^2 N_{\text{out}}^2 > k_y^2$: $\quad k_\xi = kN_{\text{out}} \cos\theta_{\text{out}}$, wave propagating at angle θ_{out},
$$N_{\text{out}} \sin\theta_{\text{out}} = N_{\text{in}} \sin\theta.$$

Snell's law



- Outgoing wave $\{N_{\text{out}}; \boldsymbol{\Psi}_{\text{out}}\}$, $(\boldsymbol{E}, \boldsymbol{H}) \sim \boldsymbol{\Psi}_{\text{out}}(\,.\,)\, \mathrm{e}^{-\mathrm{i}\,(k_y y + k_\xi \xi)}$,
$$k^2 N_{\text{out}}^2 = k_y^2 + k_\xi^2, \quad k_y = kN_{\text{in}} \sin\theta.$$
- $k^2 N_{\text{out}}^2 < k_y^2$: $\quad k_\xi = -\mathrm{i}\sqrt{k_y^2 - k^2 N_{\text{out}}^2}$, ξ-evanescent wave,
  the outgoing wave does not carry optical power.

Snell's law

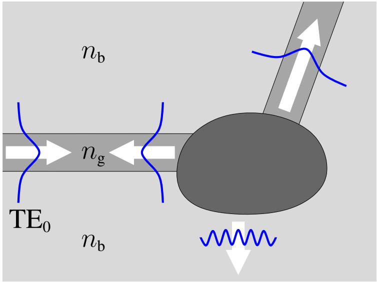


- Outgoing wave $\{N_{\text{out}}; \boldsymbol{\Psi}_{\text{out}}\}$, $\quad (\boldsymbol{E}, \boldsymbol{H}) \sim \boldsymbol{\Psi}_{\text{out}}(\,.\,)\, \mathrm{e}^{-\mathrm{i}(k_y y + k_\xi \xi)}$,

$$k^2 N_{\text{out}}^2 = k_y^2 + k_\xi^2, \quad k_y = kN_{\text{in}} \sin\theta.$$

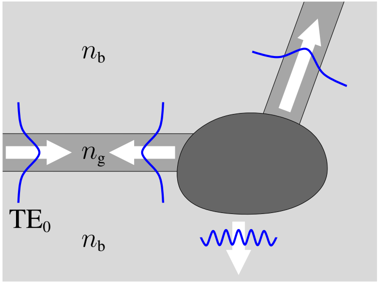
- Scan over θ:
  change from ξ-propagating to ξ-evanescent if $k^2 N_{\text{out}}^2 = k^2 N_{\text{in}}^2 \sin^2\theta$
  $\leftrightsquigarrow$ mode $\{N_{\text{out}}; \boldsymbol{\Psi}_{\text{out}}\}$ does not carry power for $\theta > \theta_{\text{cr}}$,
  critical angle θ_{cr}, $\quad \sin\theta_{\text{cr}} = N_{\text{out}}/N_{\text{in}}$.

Critical angles



$n_g > n_b$,
single mode slabs, $N_{TE0} > N_{TM0} > n_b$,
in: TE$_0$.

Critical angles



$n_g > n_b$,
single mode slabs, $N_{TE0} > N_{TM0} > n_b$,
in: TE_0.

- Propagation in the cladding relates to effective indices $N_{out} \leq n_b$
  $\rightsquigarrow$ $R_{TE0} + R_{TM0} + T_{TE0} + T_{TM0} = 1$ for $\theta > \theta_b$, $\sin\theta_b = n_b/N_{TE0}$.

- TM polarized waves relate to effective mode indices $N_{out} \leq N_{TM0}$
  $\rightsquigarrow$ $R_{TE0} + T_{TE0} = 1$, $R_{TM0} = T_{TM0} = 0$ for $\theta > \theta_m$, $\sin\theta_m = N_{TM0}/N_{TE0}$.

Formal problem, effective permittivity

$$\boldsymbol{\nabla} \times \tilde{\boldsymbol{E}} = -\mathrm{i}\omega\mu_0\tilde{\boldsymbol{H}}, \quad \boldsymbol{\nabla} \times \tilde{\boldsymbol{H}} = \mathrm{i}\omega\epsilon\epsilon_0\tilde{\boldsymbol{E}},$$

& $\partial_y \epsilon = 0,$

& $\begin{pmatrix} \tilde{\boldsymbol{E}} \\ \tilde{\boldsymbol{H}} \end{pmatrix}(x, y, z) = \begin{pmatrix} \boldsymbol{E} \\ \boldsymbol{H} \end{pmatrix}(x, z)\, \mathrm{e}^{-\mathrm{i}k_y y}, \quad k_y = kN_{\mathrm{in}} \sin\theta$

Formal problem, effective permittivity

$$\nabla \times \tilde{\boldsymbol{E}} = -\mathrm{i}\omega\mu_0\tilde{\boldsymbol{H}}, \quad \nabla \times \tilde{\boldsymbol{H}} = \mathrm{i}\omega\epsilon\epsilon_0\tilde{\boldsymbol{E}},$$

& $\quad \partial_y \epsilon = 0,$

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$$\begin{pmatrix} \partial_x \frac{1}{\epsilon}\partial_x \epsilon + \partial_z^2 & \partial_x \frac{1}{\epsilon}\partial_z \epsilon - \partial_z\partial_x \\ \partial_z \frac{1}{\epsilon}\partial_x \epsilon - \partial_x\partial_z & \partial_x^2 + \partial_z \frac{1}{\epsilon}\partial_z \epsilon \end{pmatrix}\begin{pmatrix} E_x \\ E_z \end{pmatrix} + k^2\epsilon_{\mathrm{eff}}\begin{pmatrix} E_x \\ E_z \end{pmatrix} = 0,$$

$$\epsilon_{\mathrm{eff}}(x,z) = \epsilon(x,z) - N_{\mathrm{in}}^2\sin^2\theta,$$

2-D domain, transparent-influx boundary conditions.

Formal problem, effective permittivity

$$\nabla \times \tilde{\boldsymbol{E}} = -\mathrm{i}\omega\mu_0\tilde{\boldsymbol{H}}, \quad \nabla \times \tilde{\boldsymbol{H}} = \mathrm{i}\omega\epsilon\epsilon_0\tilde{\boldsymbol{E}},$$

& $\quad \partial_y \epsilon = 0,$

& $\quad \begin{pmatrix} \tilde{\boldsymbol{E}} \\ \tilde{\boldsymbol{H}} \end{pmatrix}(x, y, z) = \begin{pmatrix} \boldsymbol{E} \\ \boldsymbol{H} \end{pmatrix}(x, z)\, \mathrm{e}^{-\mathrm{i}k_y y}, \quad k_y = kN_{\mathrm{in}} \sin\theta$

$$\begin{pmatrix} \partial_x \frac{1}{\epsilon}\partial_x \epsilon + \partial_z^2 & \partial_x \frac{1}{\epsilon}\partial_z \epsilon - \partial_z\partial_x \\ \partial_z \frac{1}{\epsilon}\partial_x \epsilon - \partial_x\partial_z & \partial_x^2 + \partial_z \frac{1}{\epsilon}\partial_z \epsilon \end{pmatrix} \begin{pmatrix} E_x \\ E_z \end{pmatrix} + k^2 \epsilon_{\mathrm{eff}} \begin{pmatrix} E_x \\ E_z \end{pmatrix} = 0,$$

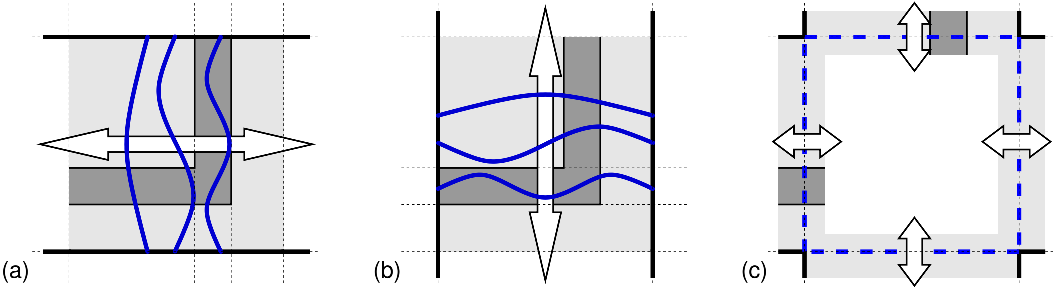
$$\epsilon_{\mathrm{eff}}(x, z) = \epsilon(x, z) - N_{\mathrm{in}}^2 \sin^2\theta,$$

2-D domain, transparent-influx boundary conditions.

- Where $\partial_x \epsilon = \partial_z \epsilon = 0$:

$$\left(\partial_x^2 + \partial_z^2\right)\phi + k^2 \epsilon_{\mathrm{eff}}\phi = 0, \quad \phi = E_j, H_j.$$

vQUEP solver



Vectorial Quadridirectional Eigenmode Propagation (vQUEP)*

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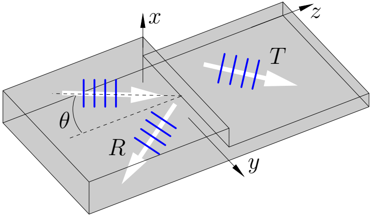
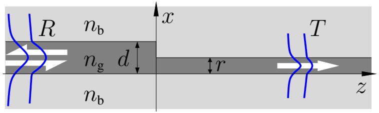
* Optics Communications 338, 447-456 (2015)

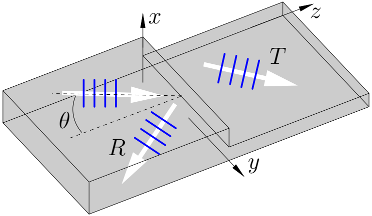
Abrupt waveguide junction

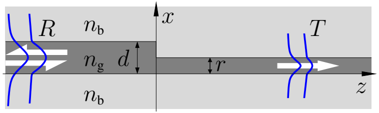


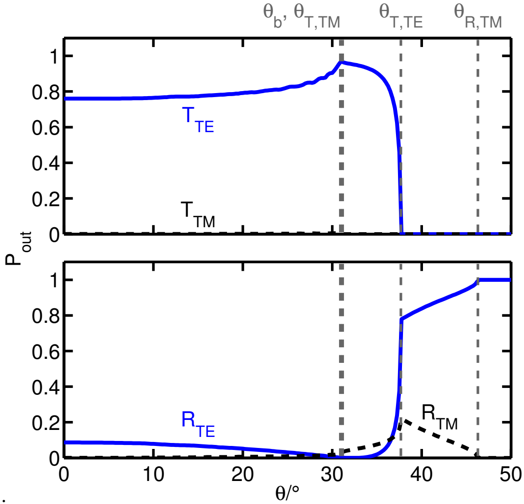


$n_b = 1.45$, $n_g = 3.45$, $d = 0.22\,\mu m$, $r = 0.05\,\mu m$,
$\lambda = 1.55\,\mu m$, in: TE_0.

Abrupt waveguide junction



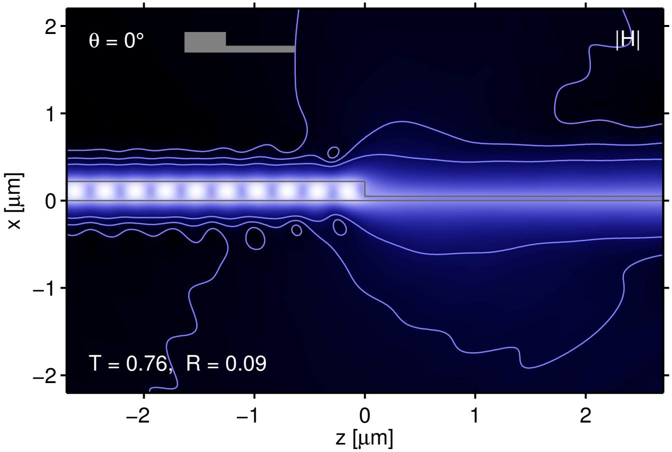




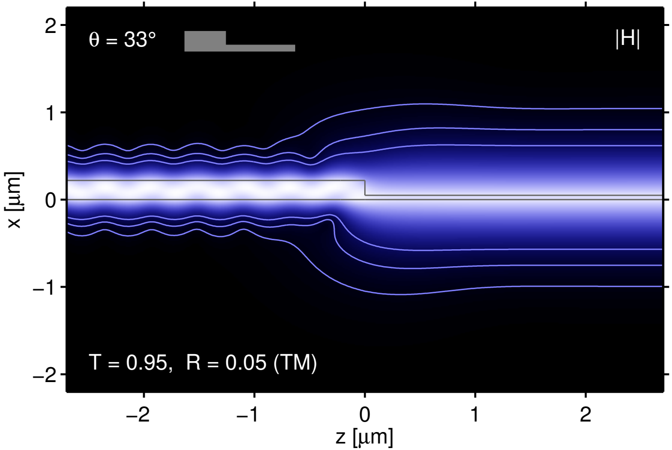
$n_b = 1.45$, $n_g = 3.45$, $d = 0.22\ \mu\text{m}$, $r = 0.05\ \mu\text{m}$,
$\lambda = 1.55\ \mu\text{m}$, in: TE_0.

$\theta_b = 30.9°$, $\theta_{T,TM} = 31.2°$, $\theta_{T,TE} = 37.7°$, $\theta_{R,TM} = 46.3°$.

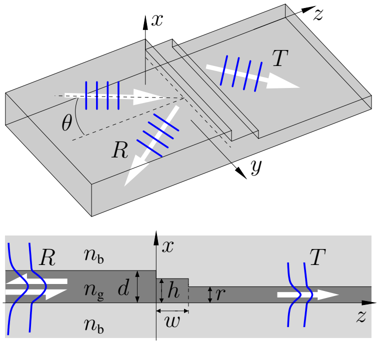
Abrupt waveguide junction, fields



Abrupt waveguide junction, fields

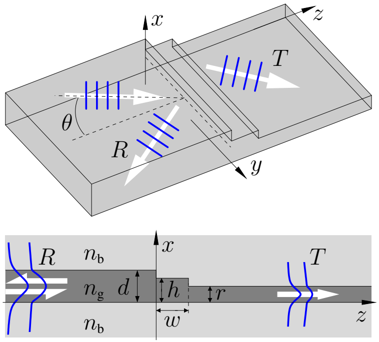


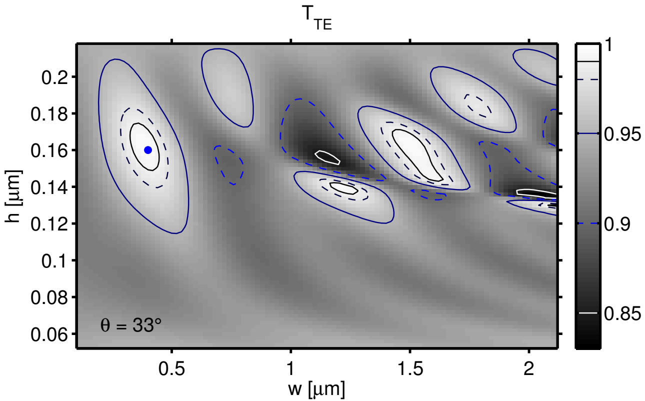
Coated waveguide junction



$n_b = 1.45$, $n_g = 3.45$, $d = 0.22$ µm, $r = 0.05$ µm,
$\lambda = 1.55$ µm, in: TE_0, $\theta = 33°$.

Coated waveguide junction





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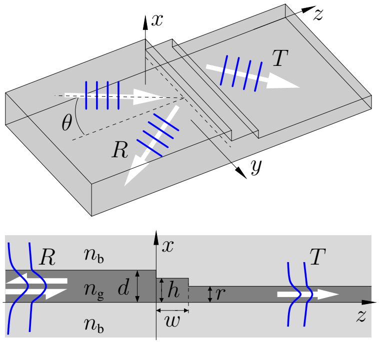
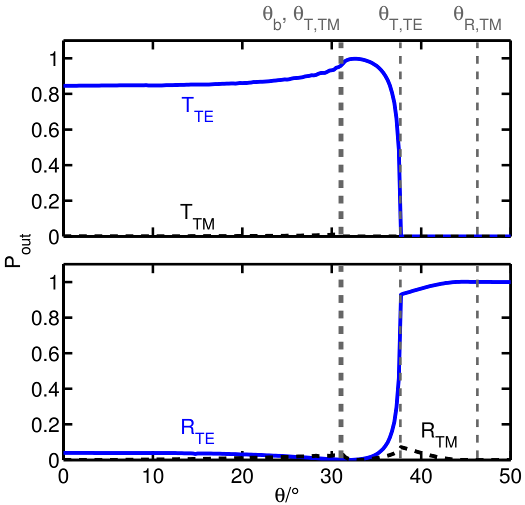
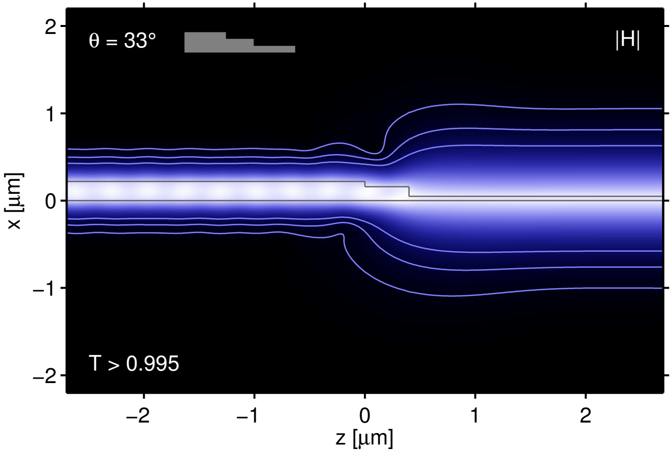




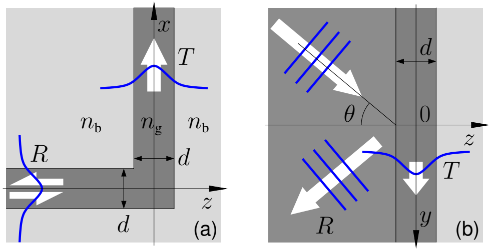
$n_b = 1.45,\ n_g = 3.45,\ d = 0.22\ \mu m,\ r = 0.05\ \mu m,$
$\lambda = 1.55\ \mu m,$ in: TE_0,
$h = 0.16\ \mu m,\ w = 0.40\ \mu m.$

$\theta_b = 30.9°,\ \theta_{T,TM} = 31.2°,\ \theta_{T,TE} = 37.7°,\ \theta_{R,TM} = 46.3°.$

Coated junction, field



Corner



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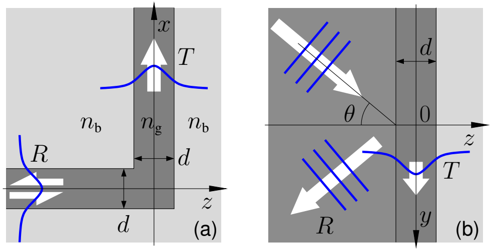
Corner



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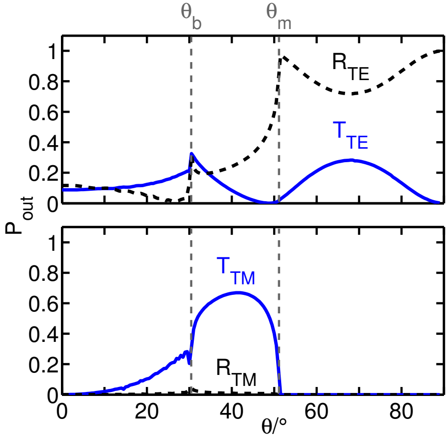
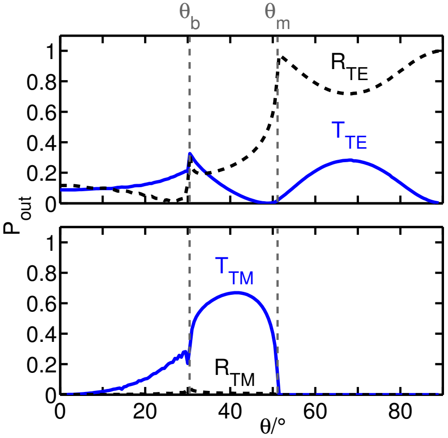
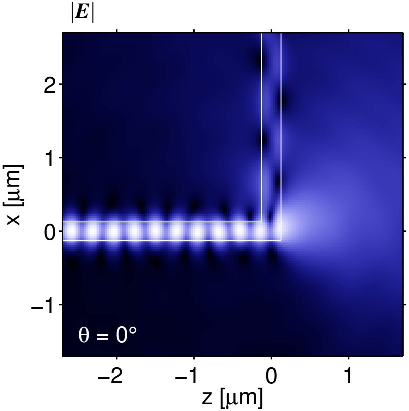


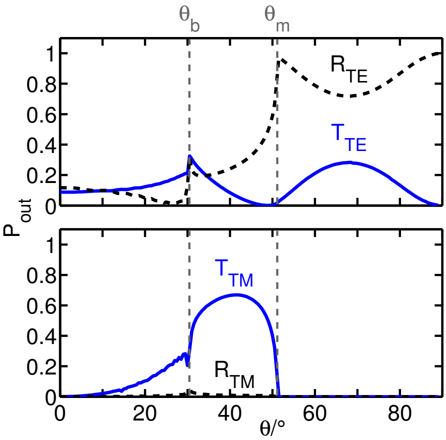
Corner

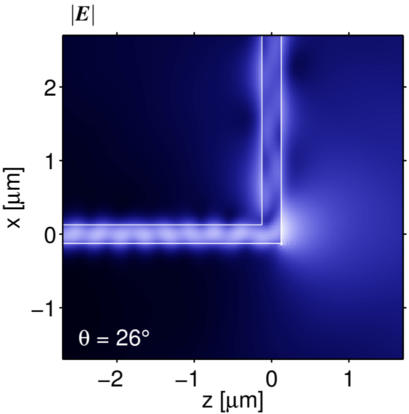




$R_{\mathrm{TE}} = 0.12, \quad R_{\mathrm{TM}} = 0,$
$T_{\mathrm{TE}} = 0.09, \quad T_{\mathrm{TM}} = 0.$

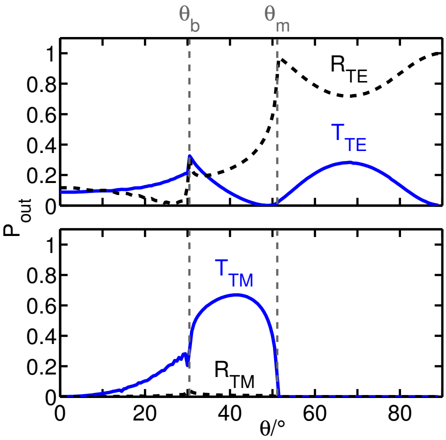
Corner

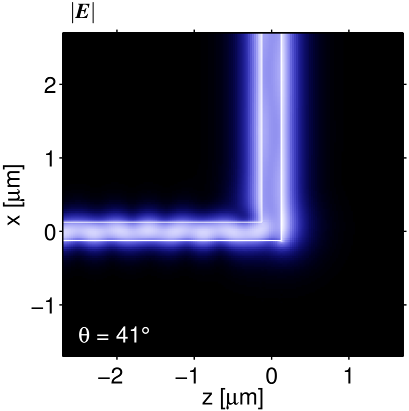




$R_{\mathrm{TE}} = 0.01, \quad R_{\mathrm{TM}} = 0.01,$
$T_{\mathrm{TE}} = 0.17, \quad T_{\mathrm{TM}} = 0.21.$

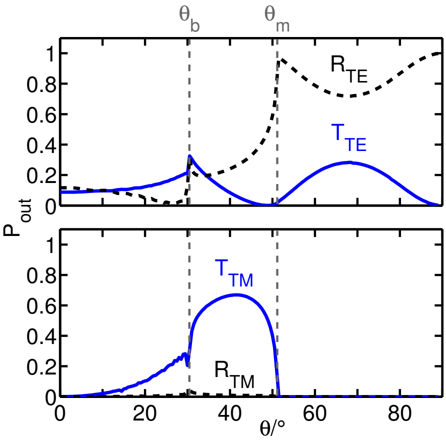
Corner

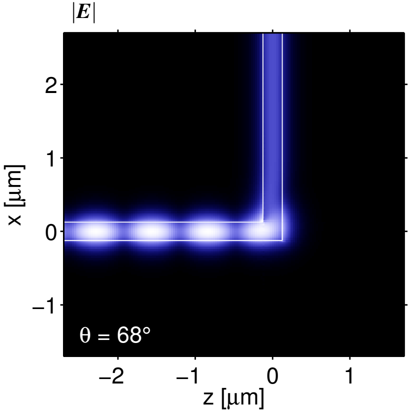




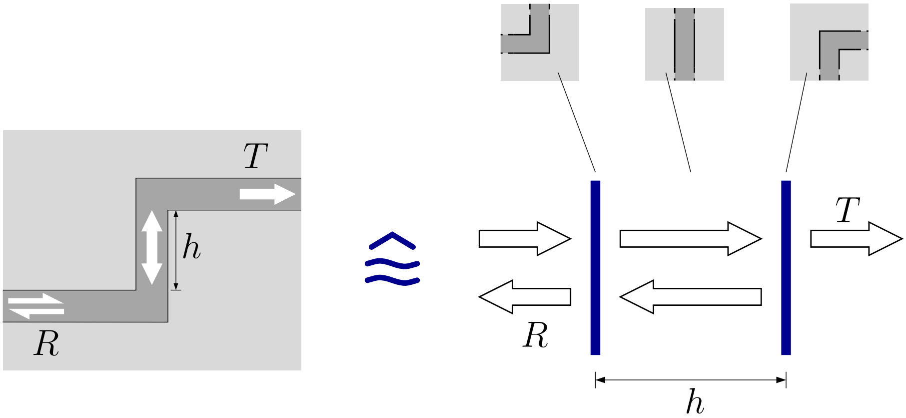
$R_{\mathrm{TE}} = 0.25, \quad R_{\mathrm{TM}} = 0.01,$
$T_{\mathrm{TE}} = 0.07, \quad T_{\mathrm{TM}} = 0.67.$

Corner

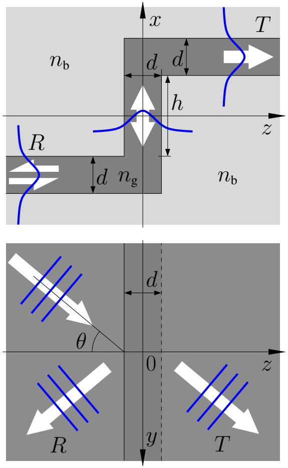




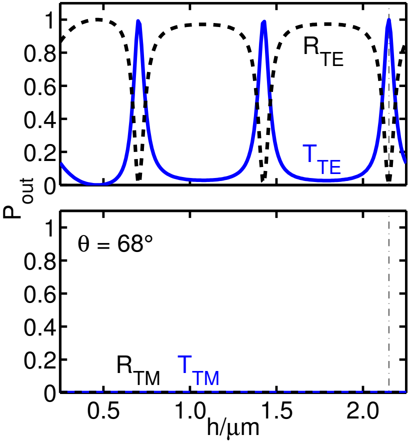
$R_{\mathrm{TE}} = 0.72, \quad R_{\mathrm{TM}} = 0,$
$T_{\mathrm{TE}} = 0.28, \quad T_{\mathrm{TM}} = 0.$


T
h
R
T
R
h

Step

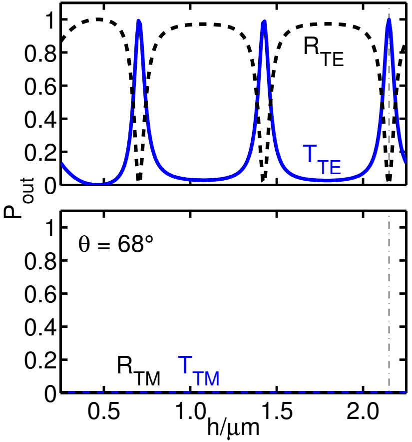


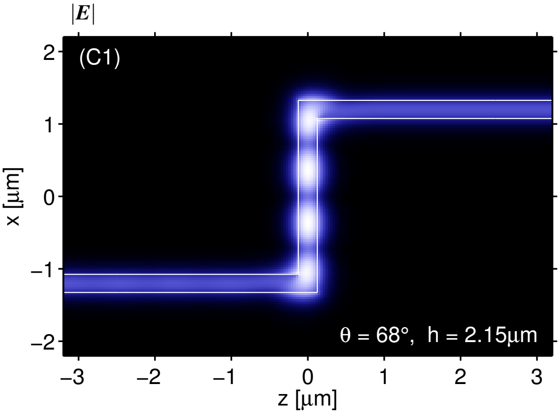
x
T
n_b
d
d
h
z
R
d
n_g
n_b
d
θ
0
z
y
R
T



P_{out}
R_{TE}
T_{TE}
θ = 68°
R_{TM}
T_{TM}
0.5
1.0
1.5
2.0
h/μm
0
0.2
0.4
0.6
0.8
1

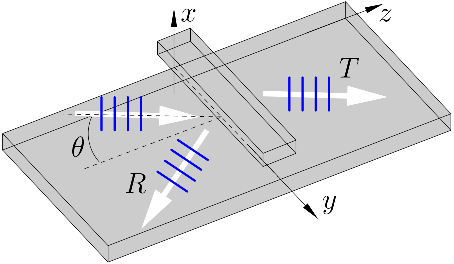
Step

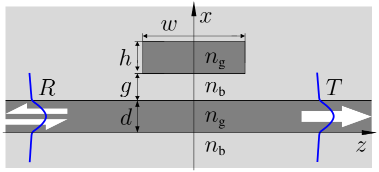




$R_{\mathrm{TE}} < 0.01, \quad R_{\mathrm{TM}} = 0,$
$T_{\mathrm{TE}} > 0.99, \quad T_{\mathrm{TM}} = 0.$

Oblique resonant excitation of a dielectric strip

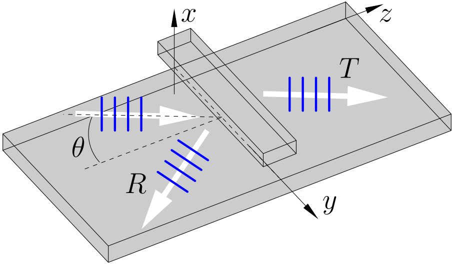


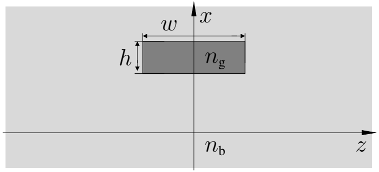


$n_g = 3.45,\ n_b = 1.45,$
$d = 0.22\ \mu m,\ \lambda = 1.55\ \mu m,$ in: TE_0;

$h = 0.22\ \mu m,\ w = 0.5\ \mu m.$

Oblique resonant excitation of a dielectric strip



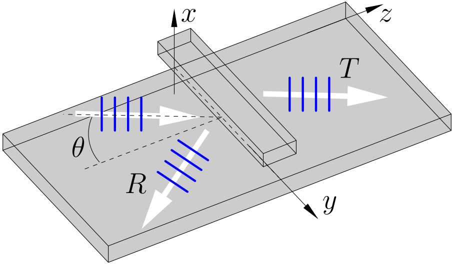


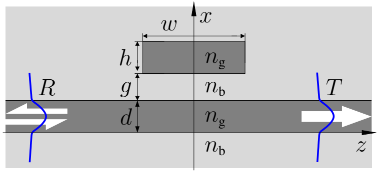
$n_{\mathrm{g}} = 3.45,\ n_{\mathrm{b}} = 1.45,$
$d = 0.22\ \mu\mathrm{m},\ \lambda = 1.55\ \mu\mathrm{m},\ \text{in: TE}_0;$

$h = 0.22\ \mu\mathrm{m},\ w = 0.5\ \mu\mathrm{m},$
$N_{\mathrm{m}} = 2.419,\ \lambda_{\mathrm{m}} = 1.55\ \mu\mathrm{m}.$

The strip supports a guided TE-like mode with effective index N_{m} @ $\lambda = \lambda_{\mathrm{m}}$.

Oblique resonant excitation of a dielectric strip





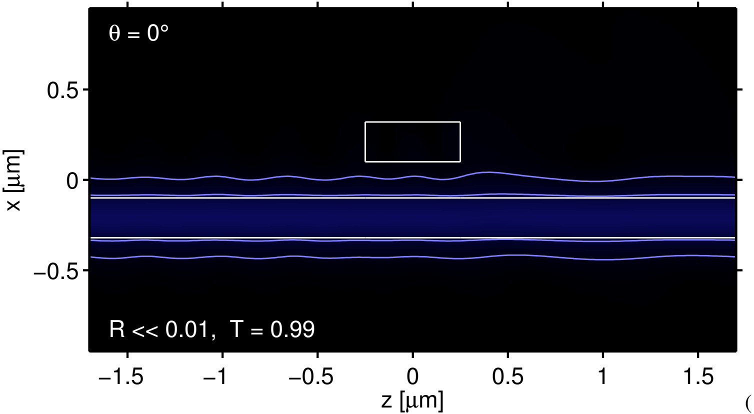
$n_g = 3.45,\ n_b = 1.45,$
$d = 0.22\ \mu\text{m},\ \lambda = 1.55\ \mu\text{m},$ in: TE_0;

$h = 0.22\ \mu\text{m},\ w = 0.5\ \mu\text{m},\ g,$
$N_m = 2.419,\ \lambda_m = 1.55\ \mu\text{m},\ \theta_m = 58.99°.$

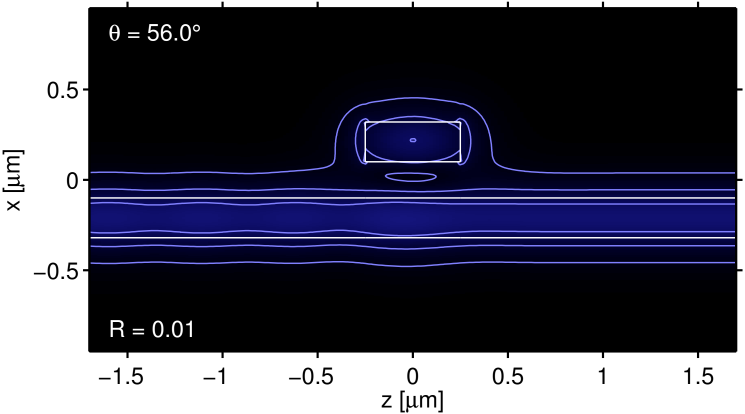
The strip supports a guided TE-like mode with effective index N_m @ $\lambda = \lambda_m$

Resonant interaction with the waves in the slab expected at $\theta \approx \theta_m$,
where $k_y = kN_{in} \sin\theta \approx kN_m$, $\sin\theta_m = N_m/N_{in}$.

Strip resonator, fields

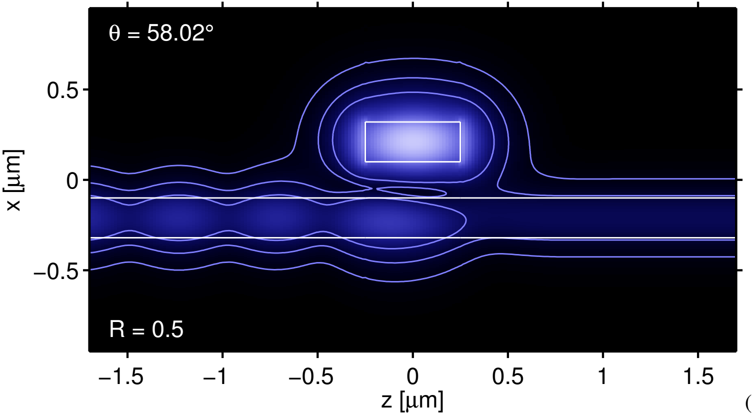


($|\boldsymbol{E}|$, $g = 200\,$nm)



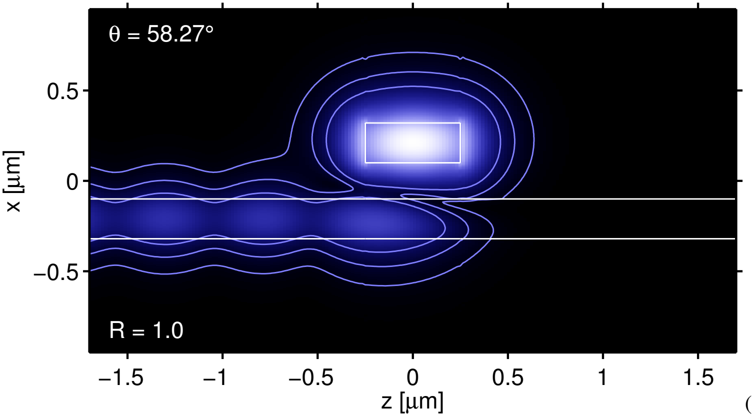
($|\boldsymbol{E}|$, $g = 200\,\mathrm{nm}$)

Strip resonator, fields



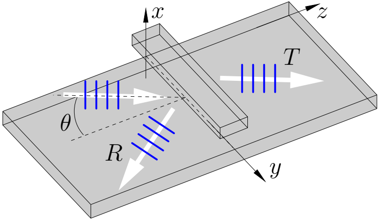
($|\boldsymbol{E}|$, $g = 200\,\mathrm{nm}$)

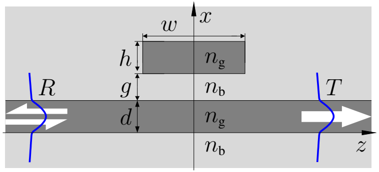
Strip resonator, fields

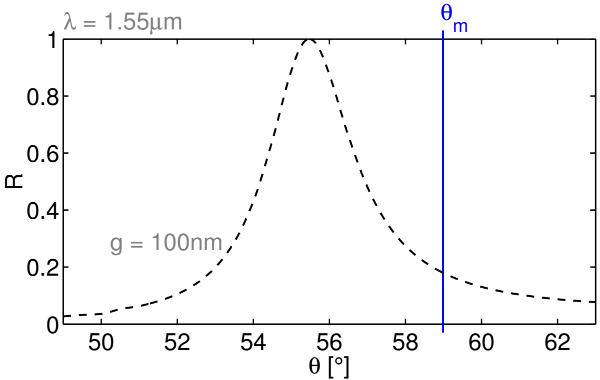


($|\boldsymbol{E}|$, $g = 200\,\mathrm{nm}$)

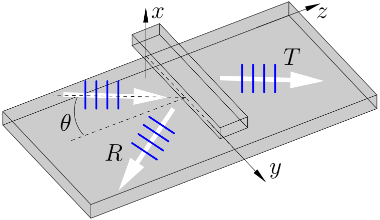
Oblique resonant excitation of a dielectric strip

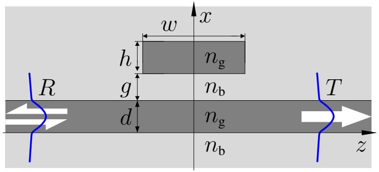


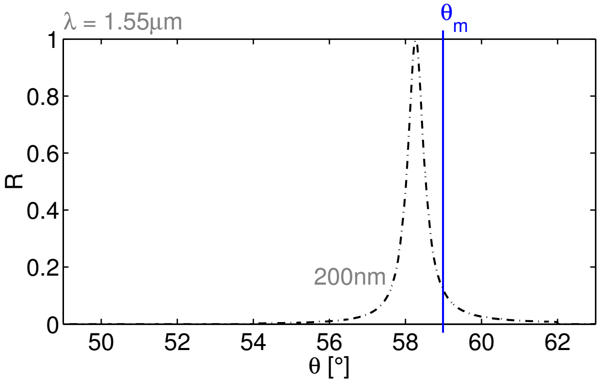




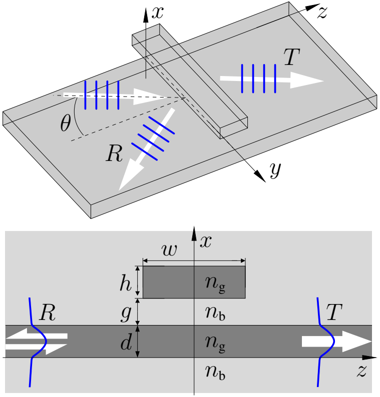
Oblique resonant excitation of a dielectric strip

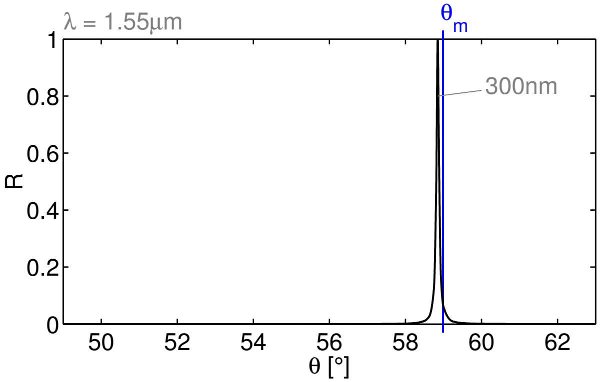




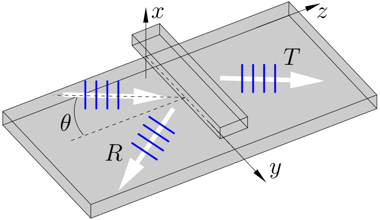


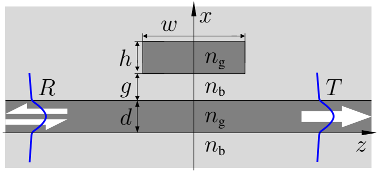
Oblique resonant excitation of a dielectric strip

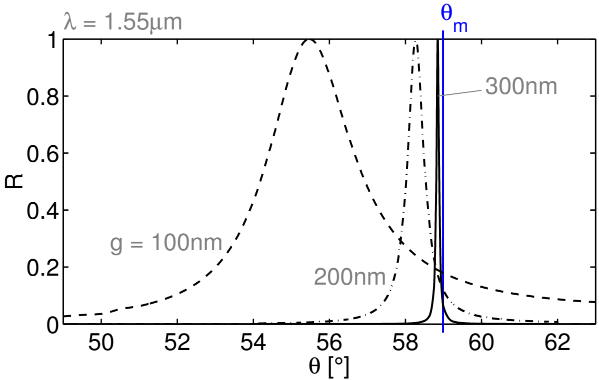




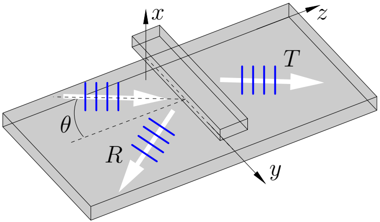
Oblique resonant excitation of a dielectric strip

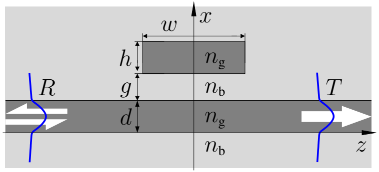


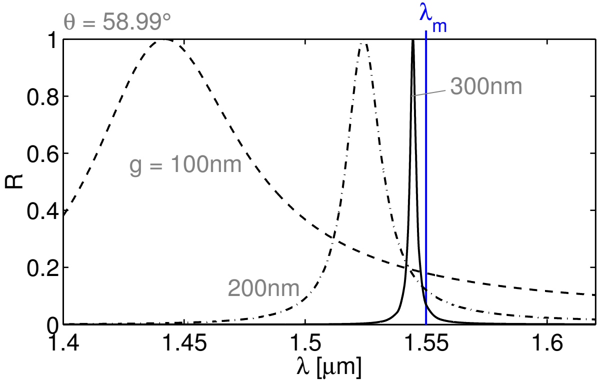




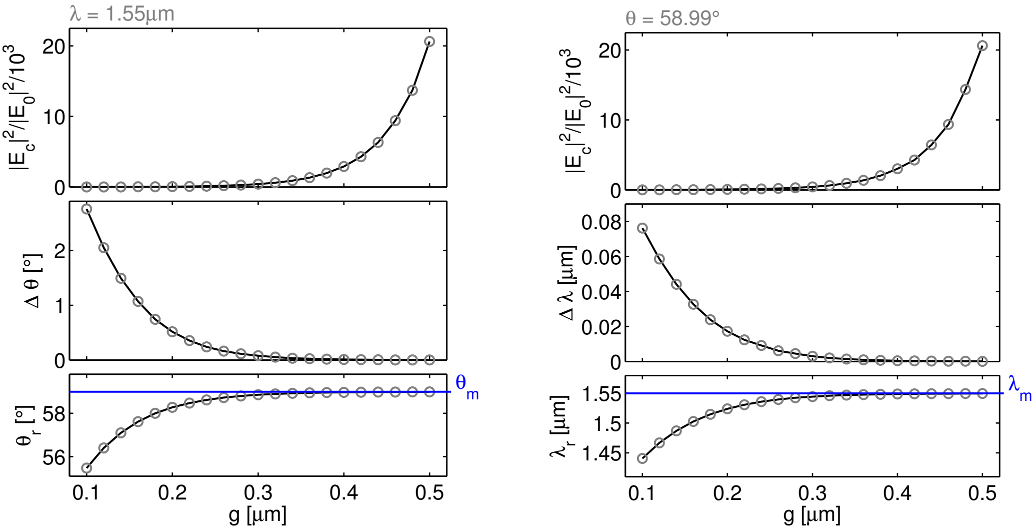
Oblique resonant excitation of a dielectric strip



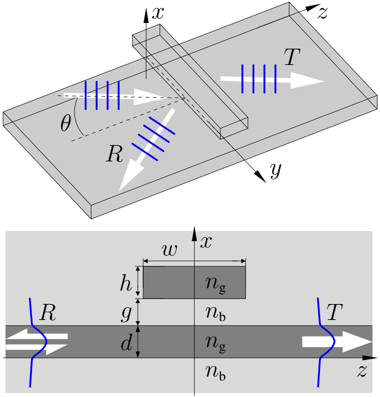


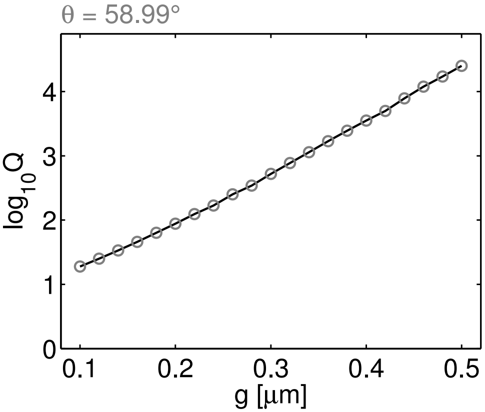


Strip resonator, resonance properties



Strip resonator, resonance properties

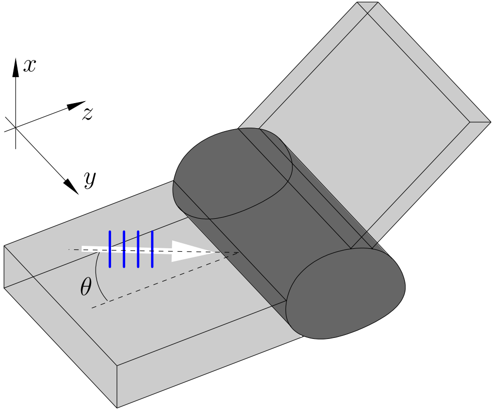




$$Q = \lambda_{\mathrm{r}}/\Delta\lambda.$$

Excitation conditions

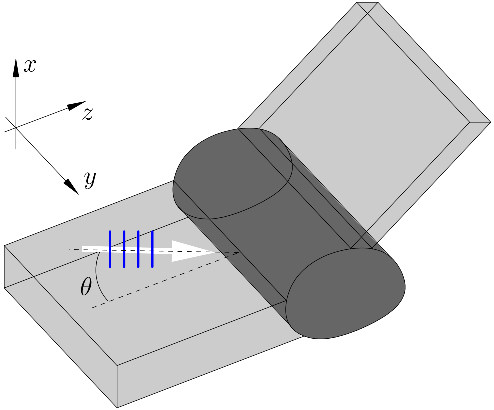
$$\partial_y \epsilon = 0$$



$$(\boldsymbol{E}_{k_y}, \boldsymbol{H}_{k_y}) \sim \mathrm{e}^{-\mathrm{i} k_y y}$$

Excitation conditions

$$\partial_y \epsilon = 0$$



$$(\boldsymbol{E}_{k_y}, \boldsymbol{H}_{k_y}) \sim \mathrm{e}^{-\mathrm{i}k_y y} \quad \rightsquigarrow \quad \int_{k_y} (\boldsymbol{E}_{k_y}, \boldsymbol{H}_{k_y})\, \mathrm{d}k_y$$

Semi-guided beams

- Superimpose 2-D solutions for a range of k_y / a range of θ, such that the input field resembles an in-plane confined beam.

$$(\boldsymbol{E}, \boldsymbol{H})\,(x, \quad z) =$$

$$\boldsymbol{\Psi}_{\text{in}}(k_y; x)\, \mathrm{e}^{-\mathrm{i}k_z(k_y)(z - z_0)} + \boldsymbol{\rho}(k_y; x, z)$$

Semi-guided beams

- Superimpose 2-D solutions for a range of k_y / a range of θ, such that the input field resembles an in-plane confined beam.

$$(\boldsymbol{E}, \boldsymbol{H})(x, y, z) =$$

$$\left(\boldsymbol{\Psi}_{\mathrm{in}}(k_y; x)\, \mathrm{e}^{-\mathrm{i} k_z(k_y)(z - z_0)} + \boldsymbol{\rho}(k_y; x, z) \right) \mathrm{e}^{-\mathrm{i} k_y (y - y_0)}$$

Semi-guided beams

- Superimpose 2-D solutions for a range of k_y / a range of θ, such that the input field resembles an in-plane confined beam.

$$(\boldsymbol{E}, \boldsymbol{H})(x, y, z) = A \int e^{-\frac{(k_y - k_{y0})^2}{w_k^2}} \left(\boldsymbol{\Psi}_{\text{in}}(k_y; x)\, e^{-\mathrm{i} k_z(k_y)(z - z_0)} + \boldsymbol{\rho}(k_y; x, z) \right) e^{-\mathrm{i} k_y (y - y_0)}\, \mathrm{d}k_y$$

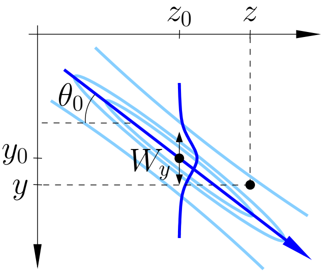
Focus at (y_0, z_0),
primary angle of incidence θ_0,
$k_{y0} = k N_{\text{in}} \sin \theta_0$.

Semi-guided beams

- Superimpose 2-D solutions for a range of k_y / a range of θ, such that the input field resembles an in-plane confined beam.

- Incoming wave, "small" w_k:

$$(\boldsymbol{E},\boldsymbol{H})_{\rm in}\,(x,y,z) = \sqrt{\pi}\frac{2\,A}{W_y}\;\mathrm{e}^{-\dfrac{\left((y-y_0)-\frac{k_{y0}}{k_{z0}}(z-z_0)\right)^2}{(W_y/2)^2}}\;\boldsymbol{\Psi}_{\rm in}(k_{y0};x)\,\mathrm{e}^{-\mathrm{i}\,(k_{y0}(y-y_0)+k_{z0}(z-z_0))}$$



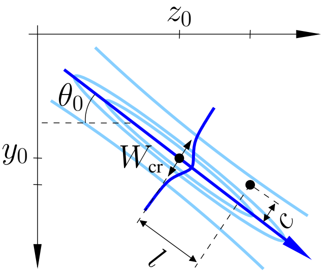
Focus at (y_0, z_0),
primary angle of incidence θ_0,
$k_{y0} = kN_{\rm in}\sin\theta_0$,
$k_{z0} = kN_{\rm in}\cos\theta_0$,
width W_y (full, along y, 1/e, field, at focus),

$W_y = 4/w_k$.

Semi-guided beams

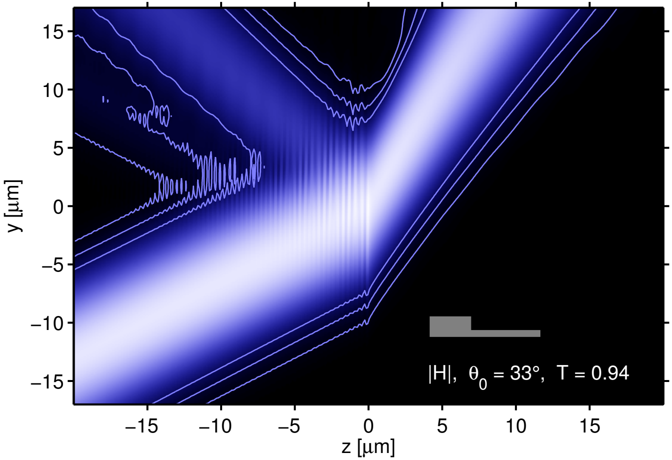
- Superimpose 2-D solutions for a range of k_y / a range of θ, such that the input field resembles an in-plane confined beam.
- Incoming wave, "small" w_k:

$$(\boldsymbol{E},\boldsymbol{H})_{\rm in}\,(x,y,z) = \sqrt{\pi}\frac{2\,A}{W_y}\;\mathrm{e}^{-\dfrac{c^2}{(W_{\rm cr}/2)^2}}\;\boldsymbol{\Psi}_{\rm in}(k_{y0};x)\;\;\mathrm{e}^{-\mathrm{i}kN_{\rm in}l}$$

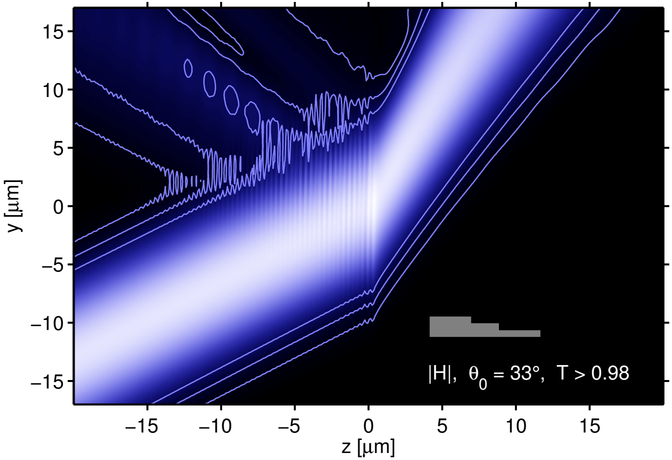


Focus at (y_0, z_0),
primary angle of incidence θ_0,
$k_{y0} = kN_{\rm in}\sin\theta_0$,
$k_{z0} = kN_{\rm in}\cos\theta_0$,
width W_y (full, along y, 1/e, field, at focus),
width $W_{\rm cr}$ (full, cross section, 1/e, field, at focus),
$W_y = 4/w_k$, $W_{\rm cr} = W_y\cos\theta_0$.

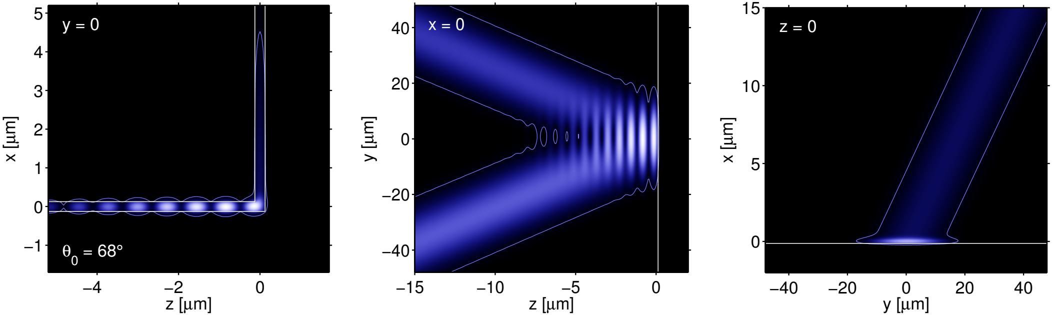
Abrupt waveguide junction, wave bundles



Coated junction, wave bundles

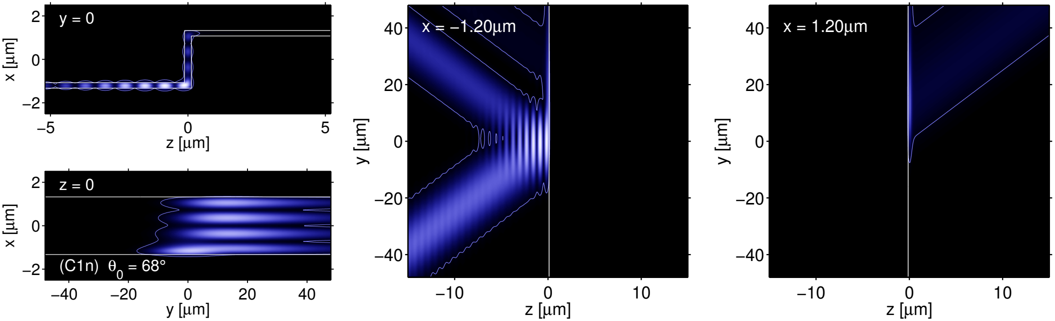


Corner, wave bundles



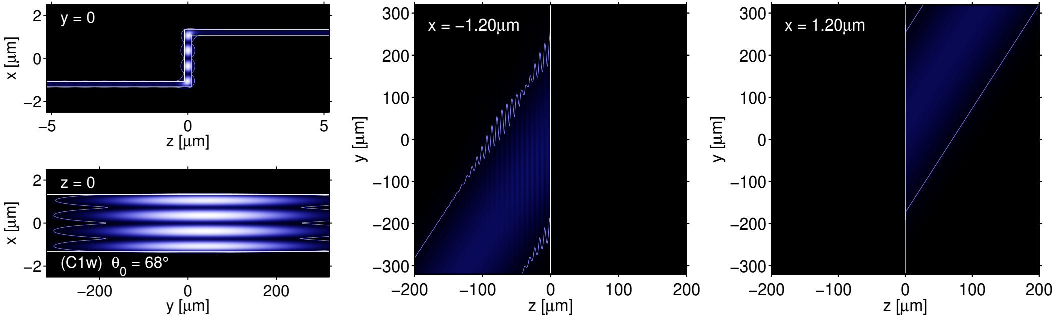
$W_y = 27\ \mu\text{m}$, $W_{\text{cr}} = 10\ \mu\text{m}$, $R_{\text{TE}} = 0.72$, $R_{\text{TM}} = 0$, $T_{\text{TE}} = 0.28$, $T_{\text{TM}} = 0$.

Step, wave bundles



$\theta_0 = 68^\circ,\ W_y = 27\ \mu\text{m},\ W_{\text{cr}} = 10\ \mu\text{m},\quad R_{\text{TE}} = 0.66,\ R_{\text{TM}} = 0,\ T_{\text{TE}} = 0.34,\ T_{\text{TM}} = 0.$

Step, wave bundles



$\theta_0 = 68°$, $W_y = 481$ µm, $W_{cr} = 180$ µm, $R_{TE} = 0.03$, $R_{TM} = 0$, $T_{TE} = 0.97$, $T_{TM} = 0$.

Oblique semi-guided waves

Early concepts of integrated optics in a high-contrast framework:

- short, quasi-lossless tapers,
- optical vias,
- open dielectric resonators with infinite Q, “bound states in a continuum” (BICs)
- . . . ? (. . . exceptionally simple structures).