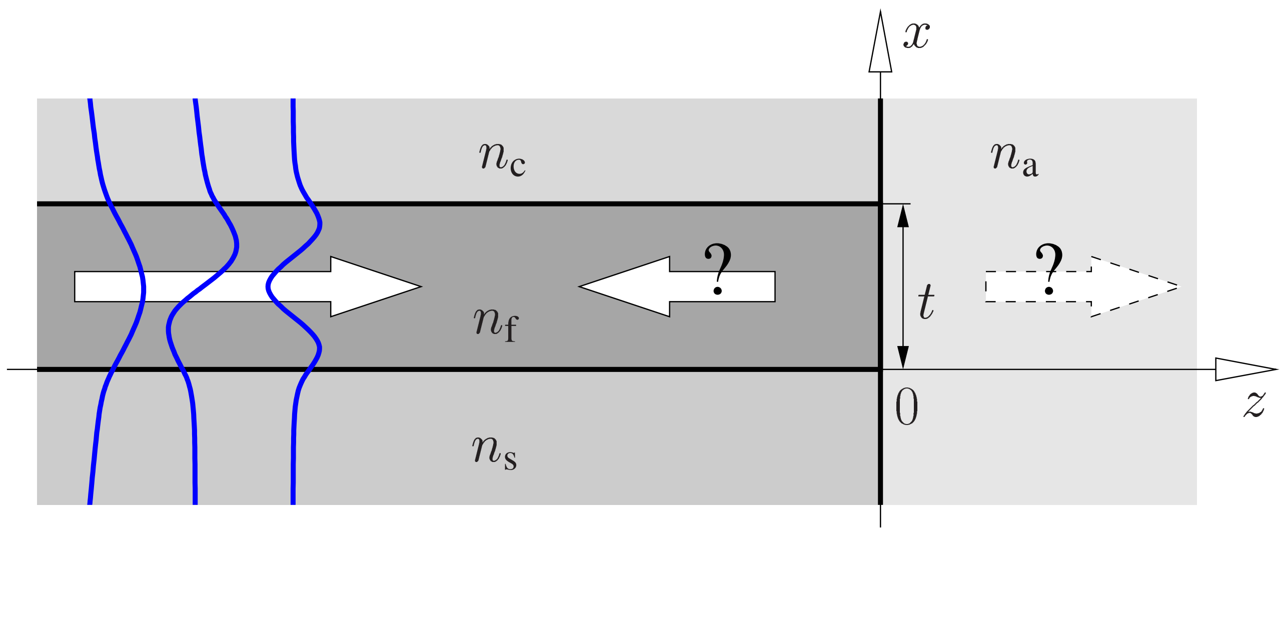
1 Guided wave reflection at slab waveguide facets

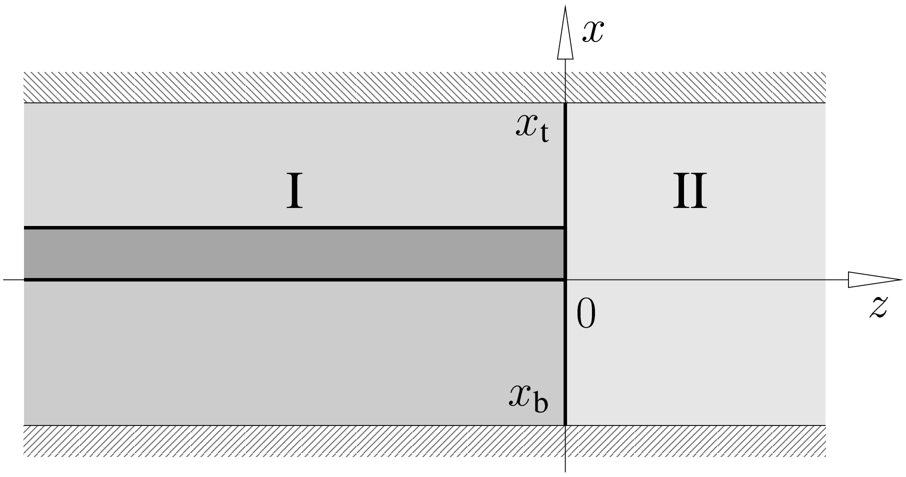
Based on rigorous mode expansion simulations, we consider the problem of guided light reflection at rectangular facets of planar dielectric waveguides. Emphasis is on multimode structures with high refractive index contrast and on configurations that show a high reflectivity.

Given the matrix of reflection coefficients for the guided fields, one can compute the maximum power reflectance for an incident mode superposition. While even for a substantial refractive index contrast across the facet the maximum reflected power for a single incoming mode is always moderate, the reflectivity may rise to a level that justifies the attribute *total*, if one considers specific superpositions of at least two guided modes. Roughly, such a configuration can be realized if the following conditions are satisfied: First, the mode angles associated with both modes in the core material have to be larger than the critical angle for total reflection at the facet. Second, the relative amplitude of the incoming fields is such that the superposition vanishes at the edges of the core at the facet.

The poster shows the results of numerical experiments for two series of symmetrical and nonsymmetrical waveguides. The observations allow at least a qualitative understanding of the pronounced resonance phenomena in some recently discussed microresonator devices, where a rectangular segment of such a high contrast multimode waveguide serves as the cavity.



2 Mode expansion simulations



Modeling steps:

- Spatial 2D setting, fixed angular frequency ω / vacuum wavelength λ.
- Division into z-homogeneous segments I, II.
- Artificial boundaries at x_b, x_t $\rightarrow$ discretization of the mode spectrum.
- Mode expansion ansatz on segments $s = \mathrm{I}, \mathrm{II}$:

$$\begin{pmatrix} \boldsymbol{\mathcal{E}} \\ \boldsymbol{\mathcal{H}} \end{pmatrix}^{s}(x,z,\tau) = \sum_m F_m^s \boldsymbol{\psi}_m^{s,\mathrm{f}}(x)\,\mathrm{e}^{\mathrm{i}\omega\tau - \mathrm{i}\beta_m^s z} + \sum_m B_m^s \boldsymbol{\psi}_m^{s,\mathrm{b}}(x)\,\mathrm{e}^{\mathrm{i}\omega\tau + \mathrm{i}\beta_m^s z}.$$

  $\{\boldsymbol{\psi}_m^{s,\mathrm{f}}, \boldsymbol{\psi}_m^{s,\mathrm{b}}\}$: forward + backward, propagating + evanescent terms.

- Inner product for overlap computations + orthogonality relations
  $\rightarrow$ bidirectional field expansions at the junction,
  $\rightarrow$ linear set of equations for $\{F_m^s, B_m^s\}$.
- $F_m^\mathrm{I} = a_m$ given, $B_m^\mathrm{II} = 0$; $B_m^\mathrm{I}, F_m^\mathrm{II} = \,?$

Uniform parameters for all simulations on this poster: 115 expansion terms, $x_\mathrm{t} - x_\mathrm{b} = 16\,\mu$m.

Rigorous numerical basis.

3 *Modal reflectivity*

Guided part of the optical field:

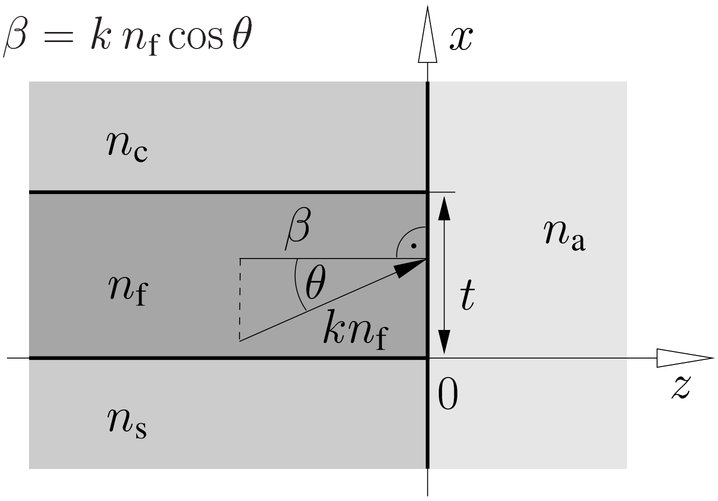
TE polarization,
electric field at time τ:
$\boldsymbol{\mathcal{E}} = (0, \mathcal{E}_y, 0)$

$$\mathcal{E}_y(x,z,\tau) = \sum_m a_m E_{y,m}(x)\, \mathrm{e}^{\mathrm{i}\omega\tau - \mathrm{i}\beta^s_m z} + \sum_{m,j} r_{mj}\, a_j\, E_{y,m}(x)\, \mathrm{e}^{\mathrm{i}\omega\tau + \mathrm{i}\beta^s_m z}.$$

$E_{y,m}$, β_m: normalized planar modes / propagation constants at frequency ω,
$P_{\mathrm{in}} = \boldsymbol{a}^\dagger \boldsymbol{a}$: input power, for input amplitudes $\boldsymbol{a} = (a_m)$,
$\mathsf{R} = (r_{mj})$: matrix of reflection coefficients,
$R = \boldsymbol{a}^\dagger \mathsf{R}^\dagger \mathsf{R} \boldsymbol{a} / P_{\mathrm{in}}$: the total relative reflected guided power,
$|r_{mm}|^2$: single mode reflectivities,
R_2: restriction of R to specific two mode superpositions.

Mode angle viewpoint:

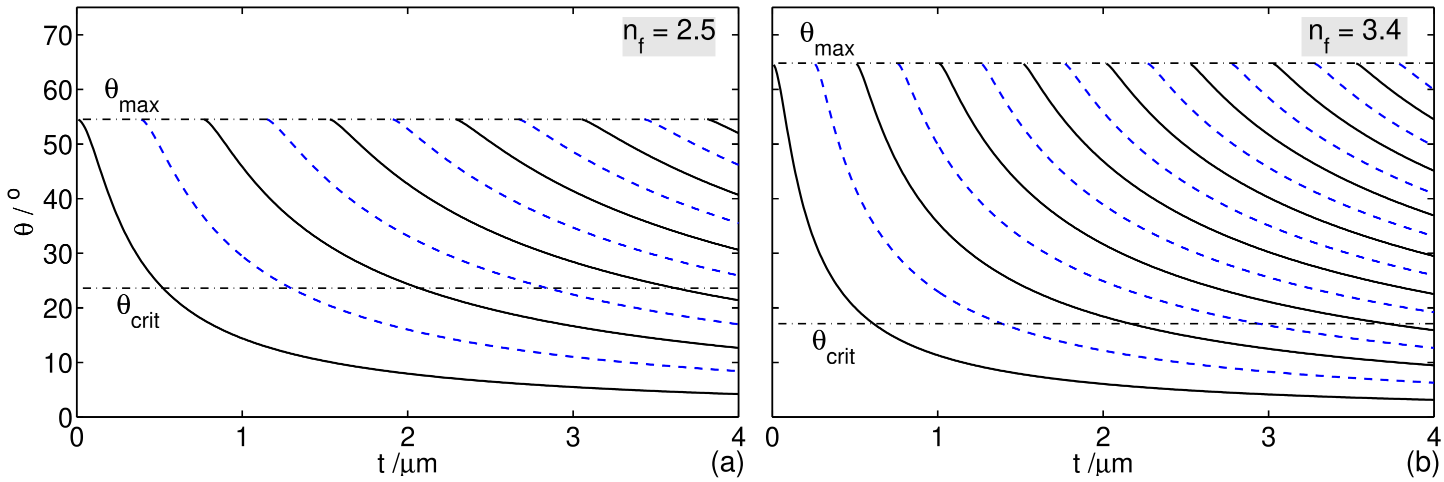
$\beta = k\, n_{\mathrm{f}} \cos\theta$



Critical angle for total reflection:
$\sin\theta_{\mathrm{crit}} = n_{\mathrm{a}}/n_{\mathrm{f}}\,.$

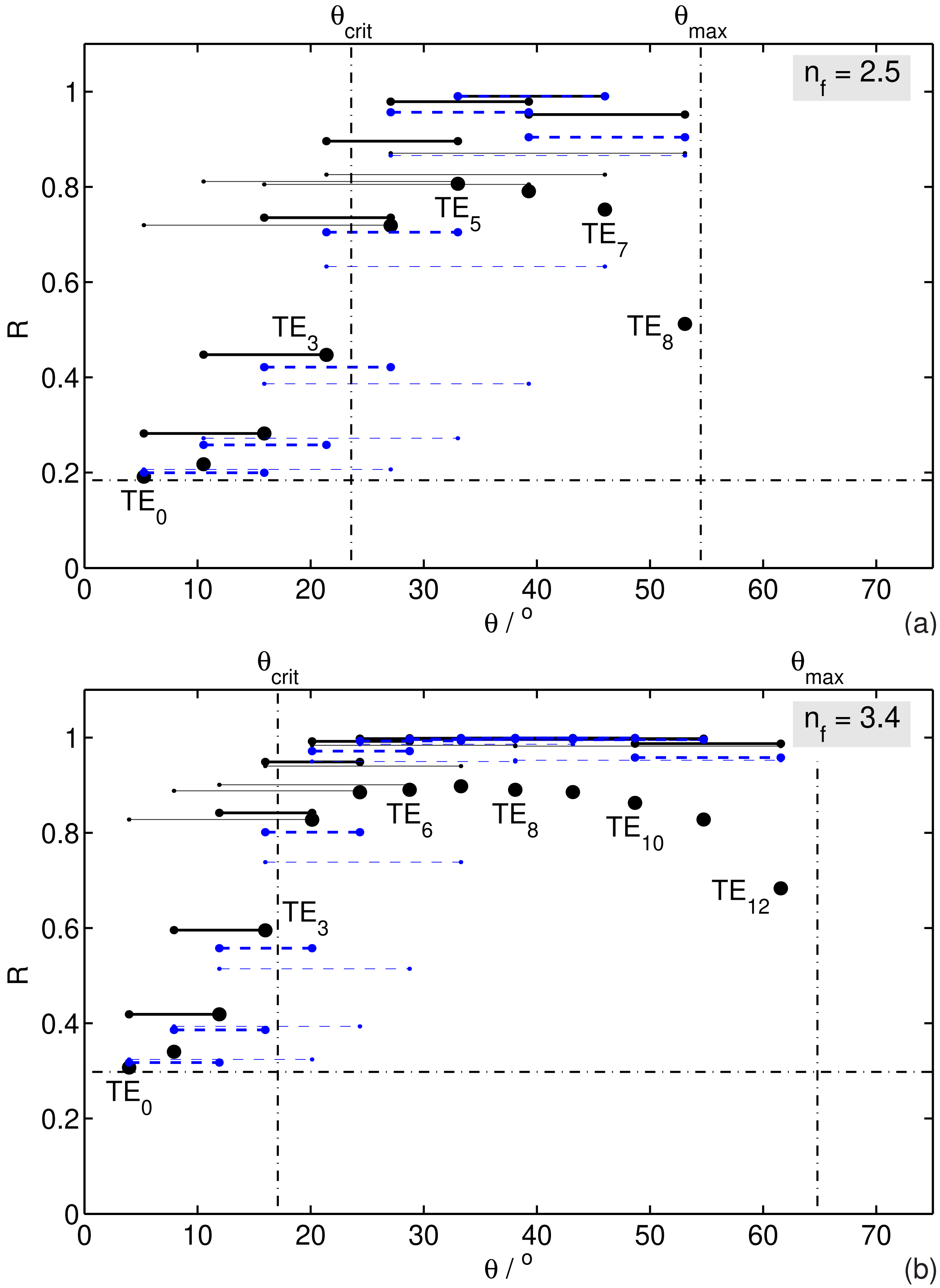
Maximum mode angle:
$\sin\theta_{\max} = \sqrt{1 - n_{\mathrm{s}}^2/n_{\mathrm{f}}^2}\,,$

High single mode reflectivity:
$\theta > \theta_{\mathrm{crit}} \;\leftrightarrow\; \beta/k < \sqrt{n_{\mathrm{f}}^2 - n_{\mathrm{a}}^2}\,,$
with $\beta/k > n_{\mathrm{s}}:\;\; n_{\mathrm{f}}^2 > n_{\mathrm{s}}^2 + n_{\mathrm{a}}^2\,.$



$n_{\mathrm{s}} = n_{\mathrm{c}} = 1.45,\;\; n_{\mathrm{a}} = 1.0,\;\; \lambda = 2\pi c/\omega = 2\pi/k = 1.55\,\mu$m.

4 Reflectivity versus mode angle



Single mode reflectivity $|r_{mm}|^2$,

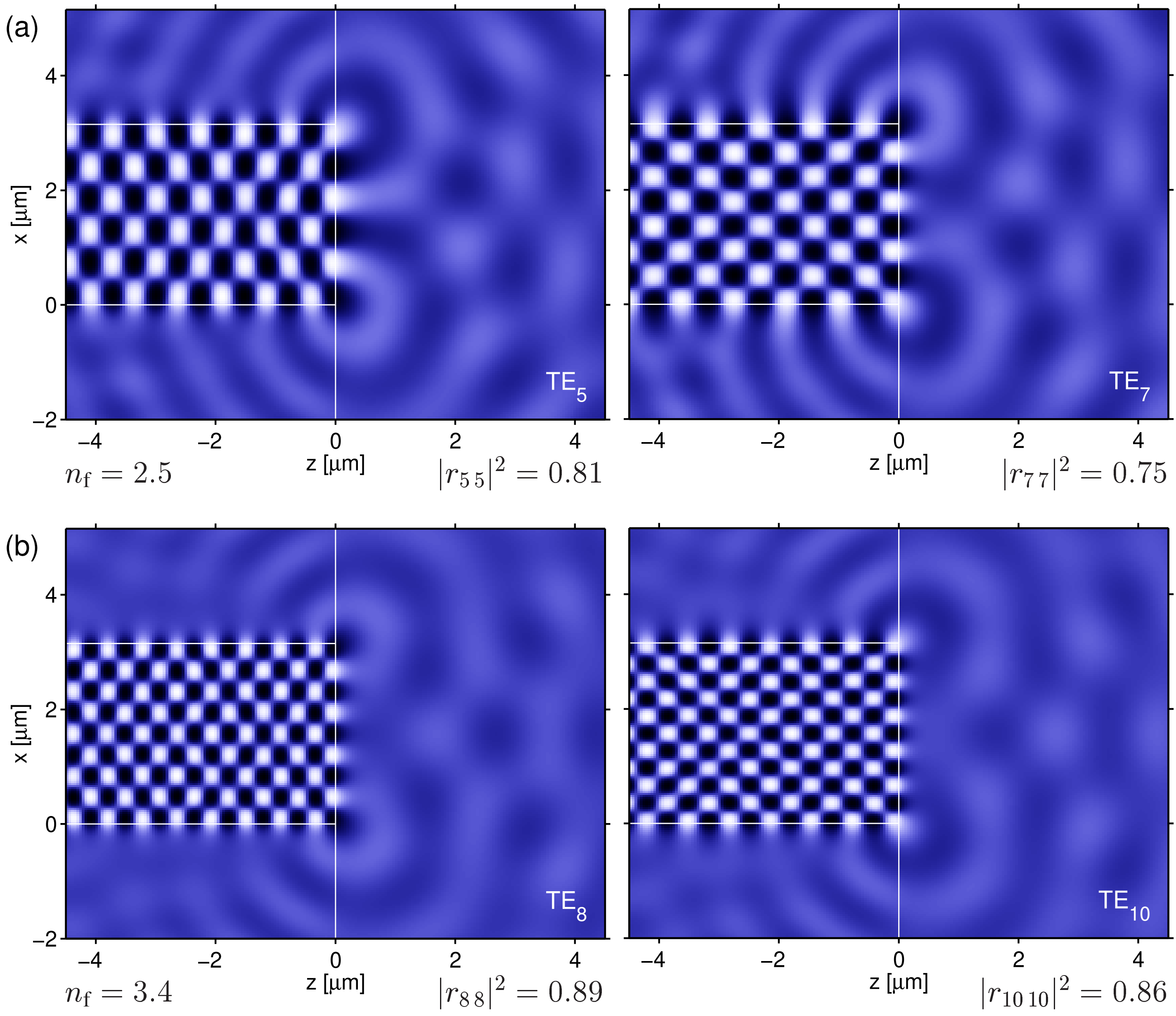
Maximum reflectivity R_2 for a two mode superposition,

Reflectivity R_2 for a two mode superposition where $\mathcal{E}_y$ vanishes at the facet edges.

$n_s = n_c = 1.45,\ n_a = 1.0,\ t = 3.15\ \mu\text{m},\ \lambda = 1.55\ \mu\text{m}.$

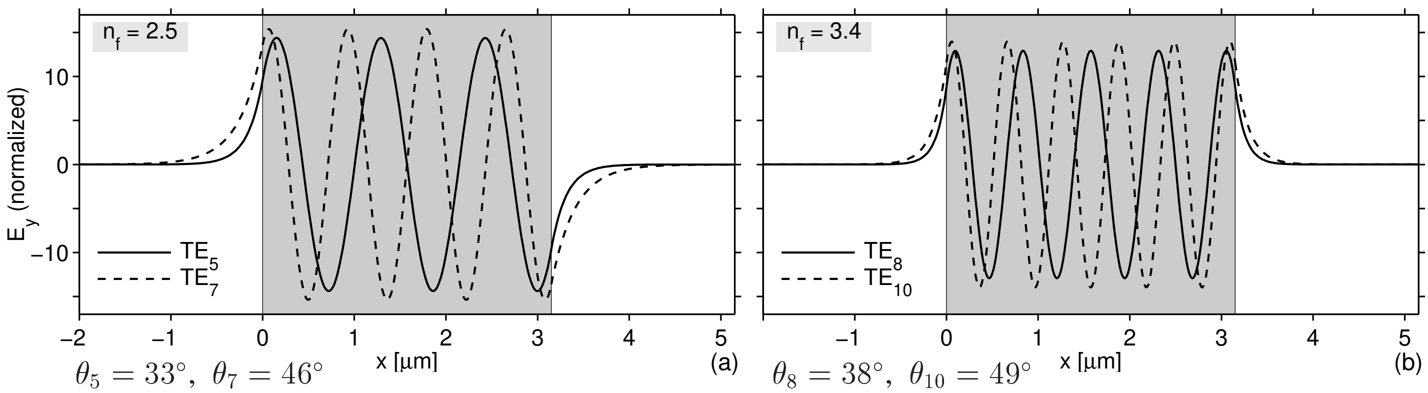
5 Single mode excitation

Extremal electric field patterns:



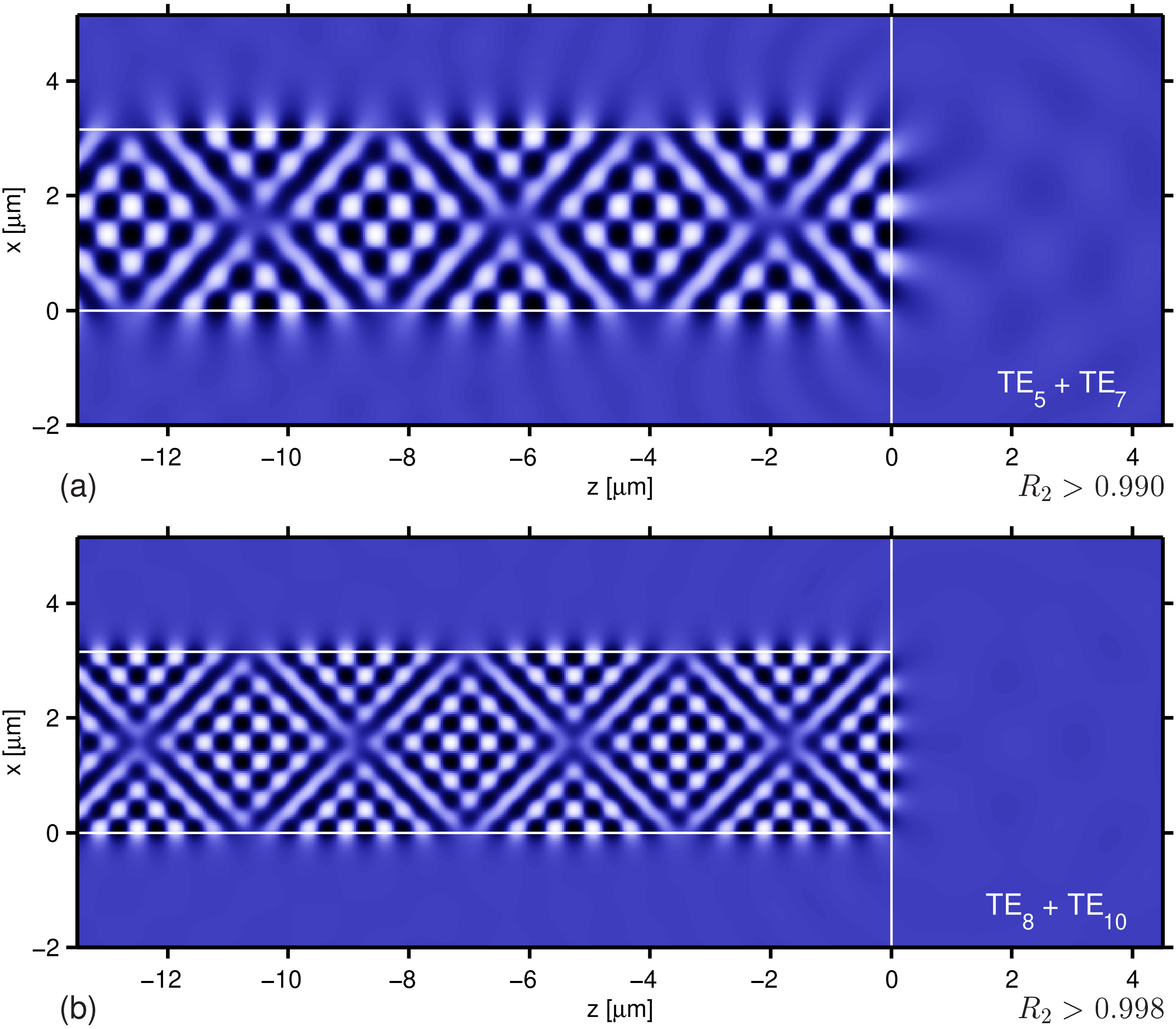
Transmission for $\theta > \theta_\mathrm{crit}$: Cylindrical waves, originating from the facet edges.

Relevant mode profiles:



6 Two mode excitation

Standing wave profiles:



$n_\mathrm{f} = 2.5$ (a), $n_\mathrm{f} = 3.4$ (b), $n_\mathrm{a} = 1.0$, $n_\mathrm{s} = 1.45$, $n_\mathrm{c} = 1.45$, $t = 3.15\,\mu$m, $\lambda = 1.55\,\mu$m.

The relative amplitude and phase of the incident modes l, m are adjusted such that the total electric field vanishes at the facet edges: $a_l = a\,a_m$ with

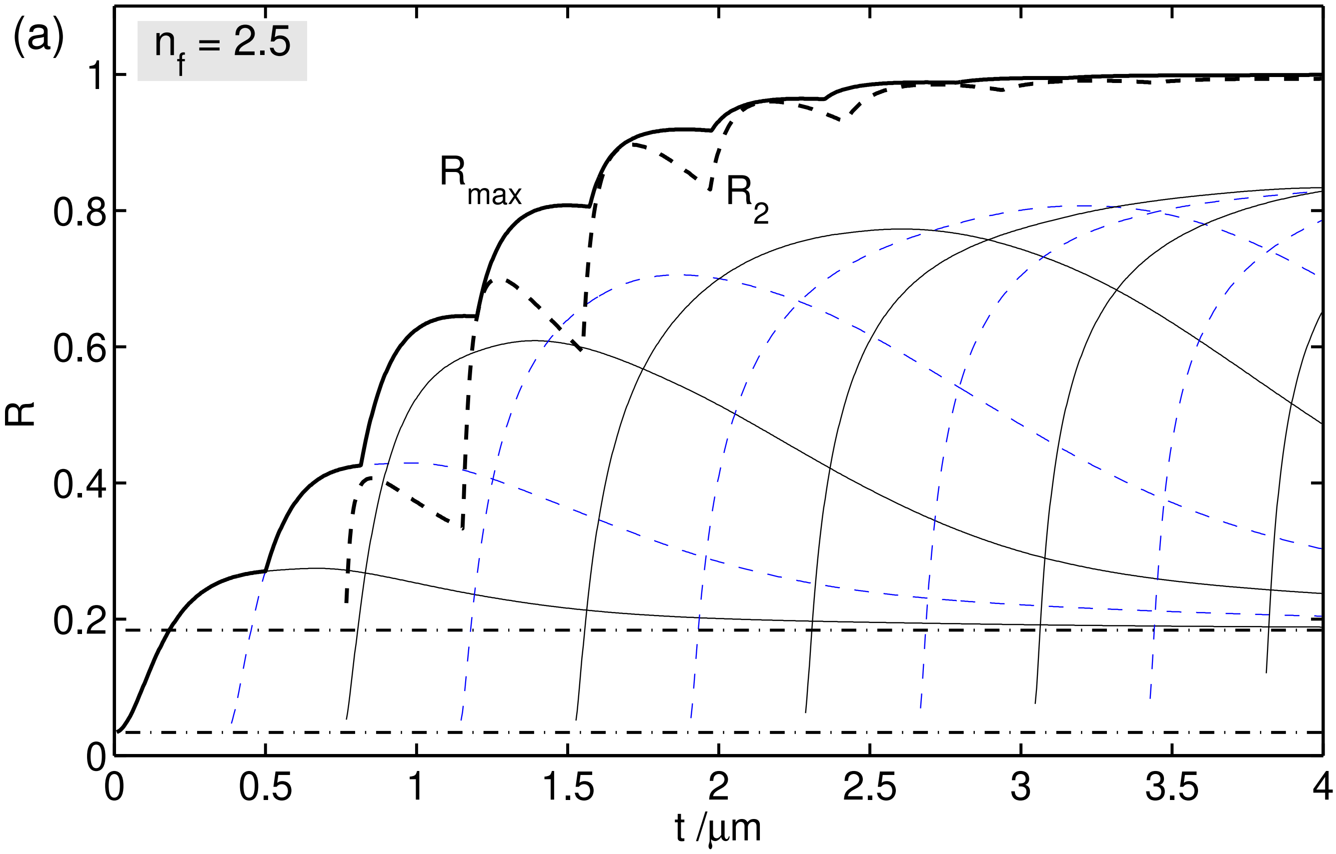
$$a = -\frac{(1 + r_{m\,m})\,E_{y,m}(0) + r_{l\,m}\,E_{y,l}(0)}{r_{m\,l}\,E_{y,m}(0) + (1 + r_{l\,l})\,E_{y,l}(0)}\,.$$

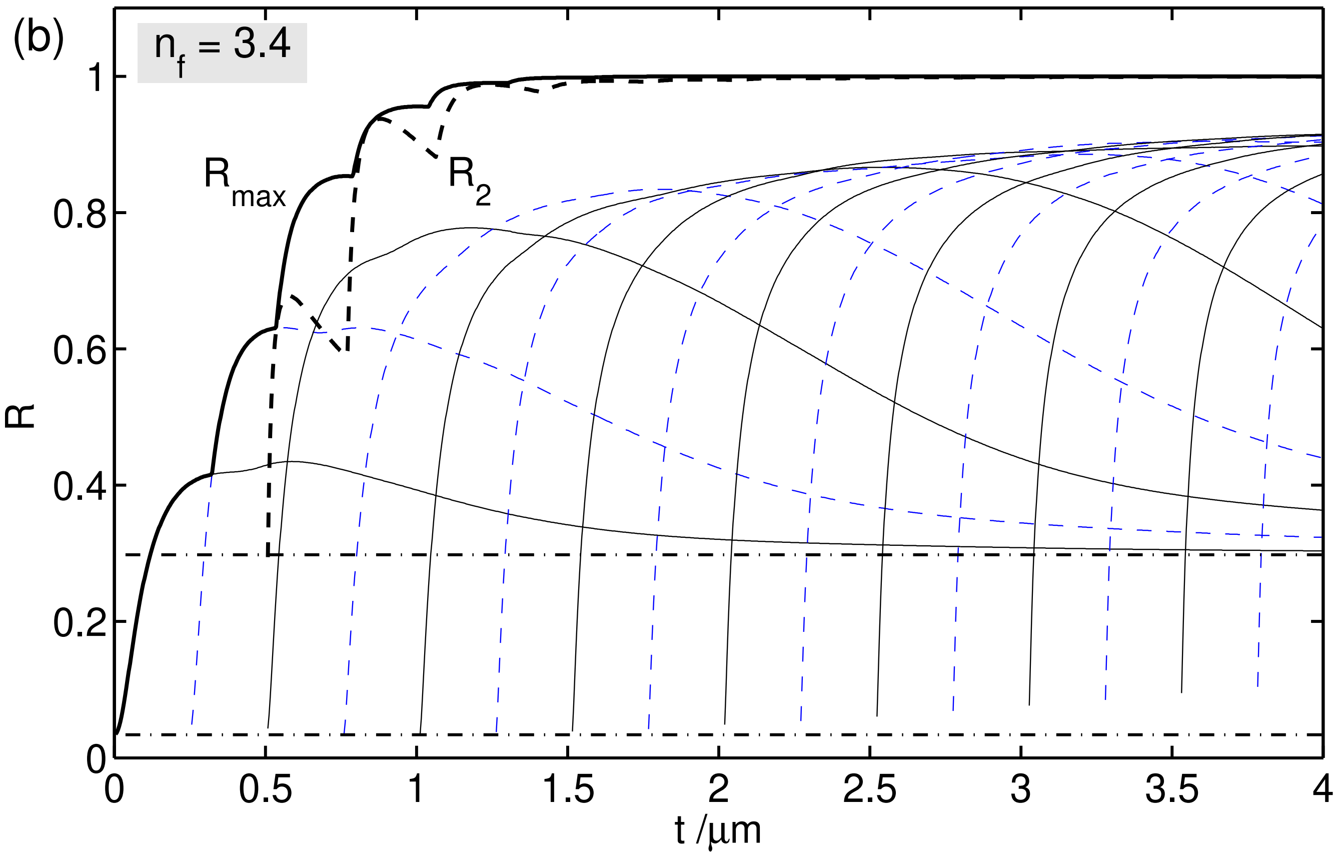
$\rightarrow$ The cylindrical waves observed for single mode incidence interfere destructively.

7 Reflectivities versus slab thickness

Symmetric waveguides

$n_{\mathrm{a}} = 1.0,\ n_{\mathrm{s}} = n_{\mathrm{c}} = 1.45,\ \lambda = 1.55\,\mu\mathrm{m},\ n_{\mathrm{f}} = 2.5$ (a), $n_{\mathrm{f}} = 3.4$ (b).

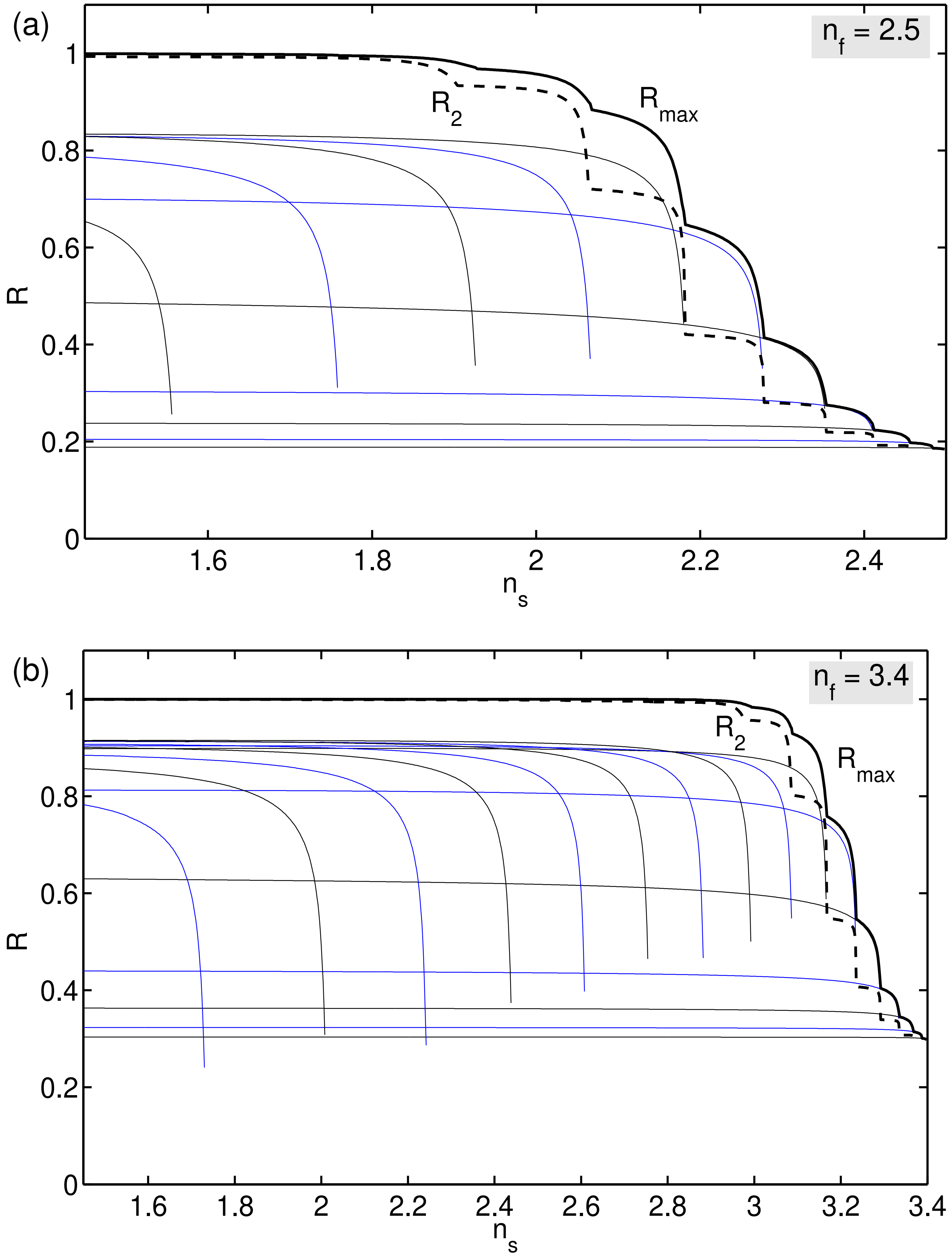




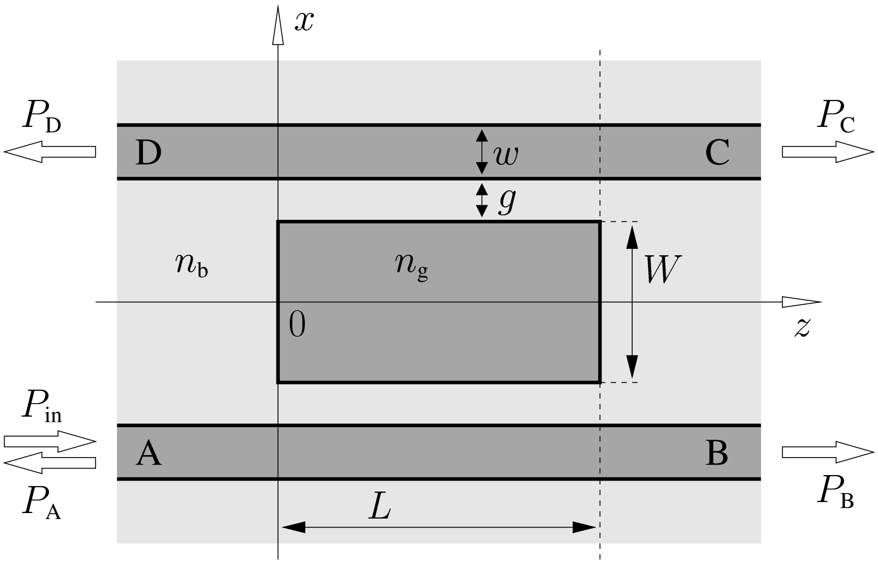
8 Reflectivities versus substrate refractive index

Nonsymmetric waveguides

$n_a = 1.0,\ n_c = 1.45,\ t = 4.0\,\mu\text{m},\ \lambda = 1.55\,\mu\text{m},\ n_f = 2.5$ (a), $n_f = 3.4$ (b).



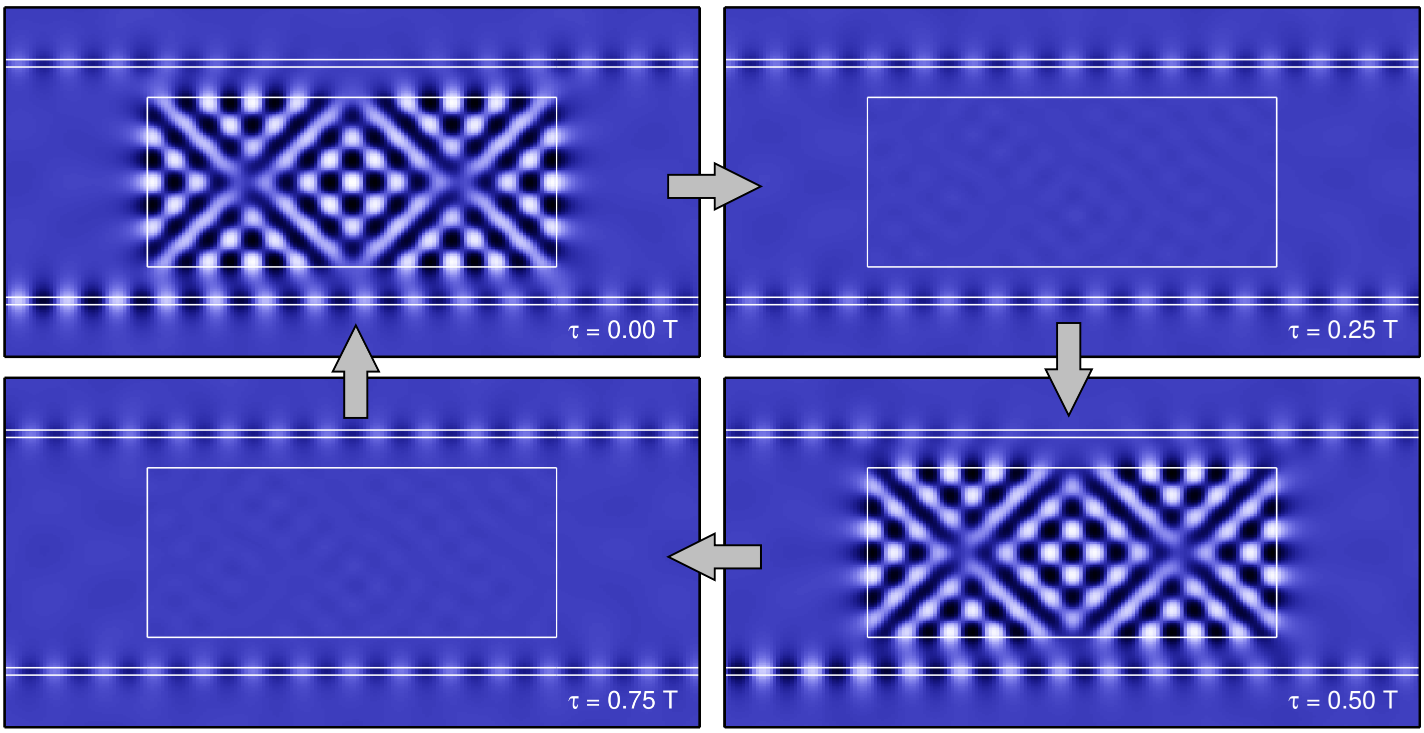
9 Motivation: Rectangular microcavities



$P_{\mathrm{in}}(\lambda) = 1.$
$P_{\mathrm{A}}, P_{\mathrm{B}}, P_{\mathrm{C}}, P_{\mathrm{D}} \ = \ ?$

$W = 2.524\,\mu\mathrm{m}, \ L = 5.738\,\mu\mathrm{m},$
$w = 0.112\,\mu\mathrm{m}, \ g = 0.450\,\mu\mathrm{m},$
$n_{\mathrm{b}} = 1.45, \ n_{\mathrm{g}} = 3.40,$
$\lambda = 1.55\,\mu\mathrm{m}.$

Resonant field pattern, time evolution:



Corresponding facet problem: