An open rectangular dielectric optical cavity with unlimited Q

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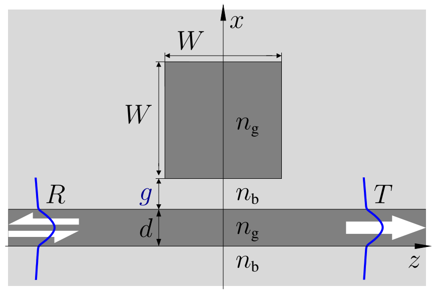
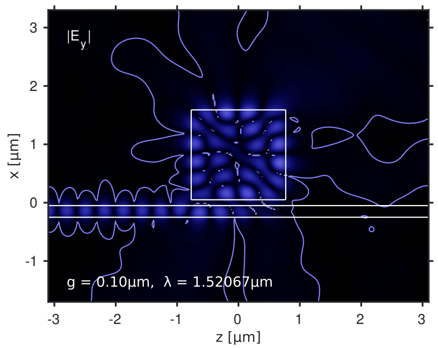
An open dielectric resonator with a rectangular cavity

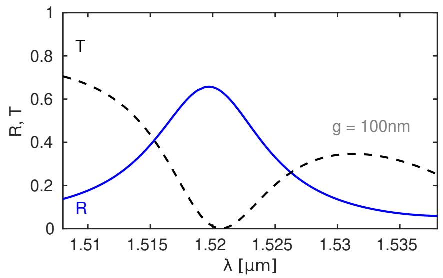


(2-D)

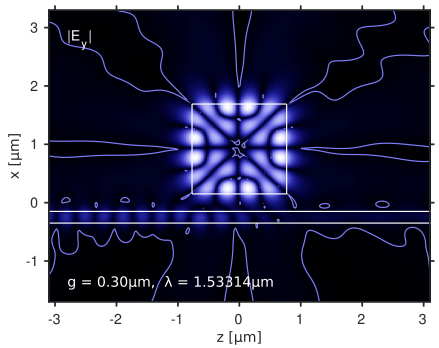
$n_g = 3.2$, $n_b = 1.0$,
$d = 0.2\,\mu$m, $W = 1.54\,\mu$m, variable g,
$\lambda \in [1.508, 1.538]\,\mu$m, in: TE_0.

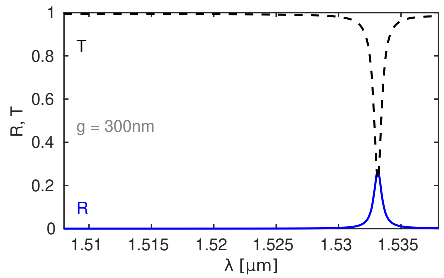
An open dielectric resonator with a rectangular cavity





An open dielectric resonator with a rectangular cavity





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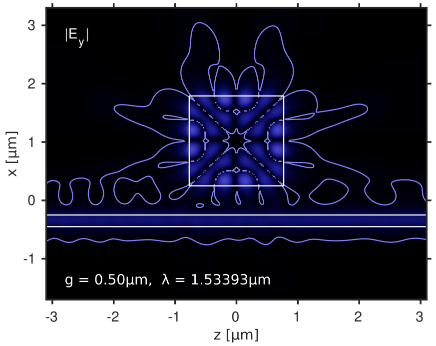
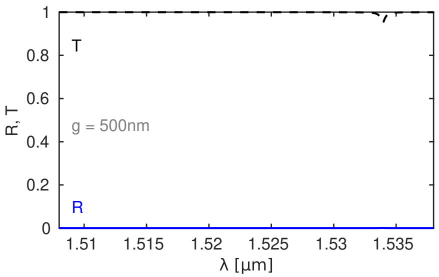
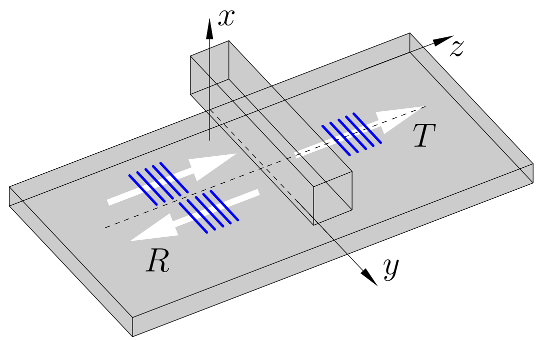




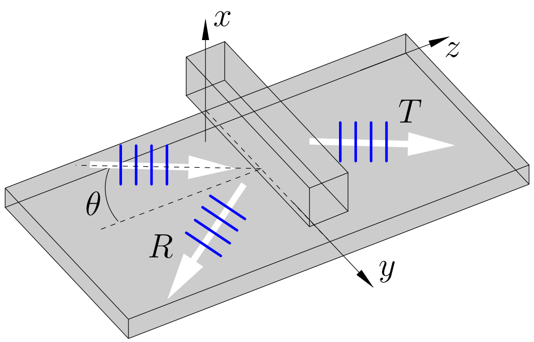
An open dielectric resonator with a rectangular cavity

(2-D) $\partial_y \epsilon = 0,\ \partial_y(\boldsymbol{E}, \boldsymbol{H}) = 0$



An open dielectric resonator with a rectangular cavity

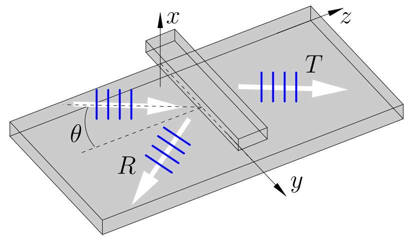
(2.5-D) $\partial_y \epsilon = 0,\ (\boldsymbol{E}, \boldsymbol{H}) \sim \exp(-\mathrm{i} k_y y),\ k_y \sim \sin\theta$



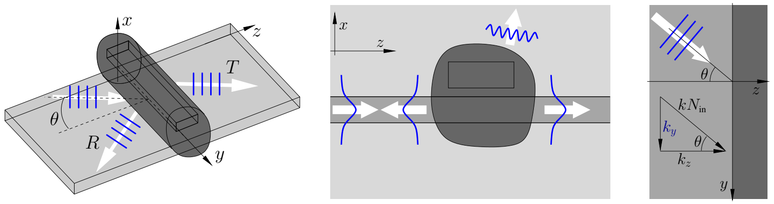
An open rectangular dielectric optical cavity with unlimited Q

Overview

- Oblique incidence of semi-guided waves
- Snell's law, critical angles
- Strip resonator, resonance properties



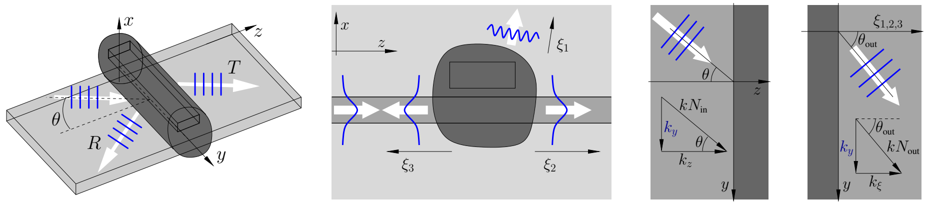
Semi guided waves at oblique angles of incidence



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

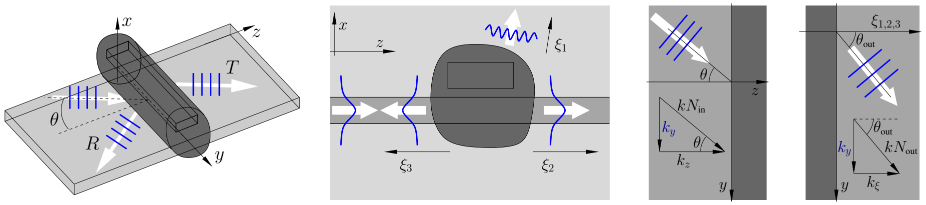
- Incoming slab mode $\{N_{\text{in}}; \mathbf{\Psi}_{\text{in}}\}$, $(\boldsymbol{E}, \boldsymbol{H}) \sim \mathbf{\Psi}_{\text{in}}(x)\, \mathrm{e}^{-\mathrm{i}(k_y y + k_z z)}$,
  incidence angle θ, $k^2 N_{\text{in}}^2 = k_y^2 + k_z^2$, $k_y = kN_{\text{in}} \sin\theta$.
- y-homogeneous problem: $(\boldsymbol{E}, \boldsymbol{H}) \sim \mathrm{e}^{-\mathrm{i}k_y y}$ everywhere.

Semi guided waves at oblique angles of incidence



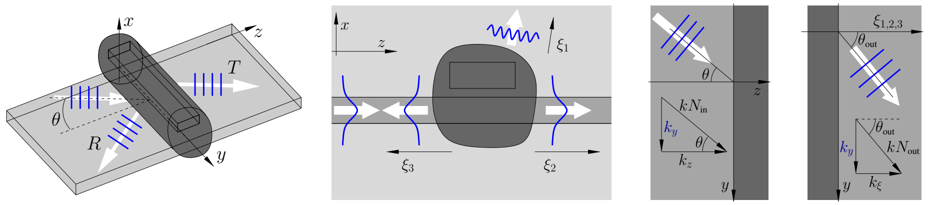
- Outgoing wave $\{N_{\text{out}}; \mathbf{\Psi}_{\text{out}}\}$, $(\boldsymbol{E}, \boldsymbol{H}) \sim \mathbf{\Psi}_{\text{out}}(\,.\,)\, \mathrm{e}^{-\mathrm{i}(k_y y + k_\xi \xi)}$,
  $k^2 N_{\text{out}}^2 = k_y^2 + k_\xi^2$, $k_y = kN_{\text{in}} \sin\theta$.
- $k^2 N_{\text{out}}^2 > k_y^2$: $k_\xi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

Semi guided waves at oblique angles of incidence



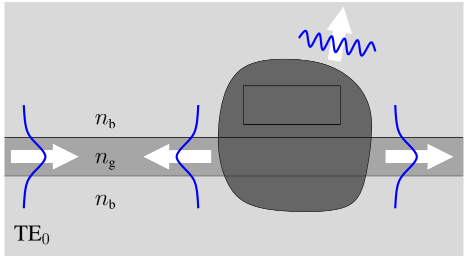
- Outgoing wave $\{N_{\text{out}}; \mathbf{\Psi}_{\text{out}}\}$, $(\boldsymbol{E}, \boldsymbol{H}) \sim \mathbf{\Psi}_{\text{out}}(\,.\,)\, \mathrm{e}^{-\mathrm{i}(k_y y + k_\xi \xi)}$,
  $k^2 N_{\text{out}}^2 = k_y^2 + k_\xi^2$, $k_y = kN_{\text{in}} \sin\theta$.
- $k^2 N_{\text{out}}^2 < k_y^2$: $k_\xi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

Semi guided waves at oblique angles of incidence



- Outgoing wave $\{N_{\text{out}}; \mathbf{\Psi}_{\text{out}}\}$, $(\boldsymbol{E}, \boldsymbol{H}) \sim \mathbf{\Psi}_{\text{out}}(\,.\,)\, \mathrm{e}^{-\mathrm{i}(k_y y + k_\xi \xi)}$,
  $k^2 N_{\text{out}}^2 = k_y^2 + k_\xi^2$, $k_y = kN_{\text{in}} \sin\theta$.
- Scan over θ:
  change from ξ-propagating to ξ-evanescent if $k^2 N_{\text{out}}^2 = k^2 N_{\text{in}}^2 \sin^2\theta$
  $\leadsto$ mode $\{N_{\text{out}}; \mathbf{\Psi}_{\text{out}}\}$ does not carry power for $\theta > \theta_{\text{cr}}$,
  critical angle θ_{cr}, $\sin\theta_{\text{cr}} = N_{\text{out}}/N_{\text{in}}$.

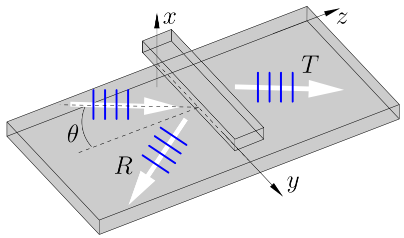
Critical angles

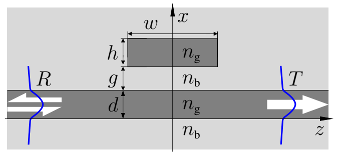


$n_g > n_b$,
single mode slabs, $N_{TE0} > N_{TM0} > n_b$,
in: TE_0.

- Propagation in the cladding relates to effective indices $N_{out} \le n_b$
  ⇝ $R_{TE0} + R_{TM0} + T_{TE0} + T_{TM0} = 1$ for $\theta > \theta_b$, $\sin\theta_b = n_b/N_{TE0}$.
- TM polarized waves relate to effective mode indices $N_{out} \le N_{TM0}$
  ⇝ $R_{TM0} = T_{TM0} = 0$, $R_{TE0} + T_{TE0} = 1$ for $\theta > \theta_{TM}$, $\sin\theta_{TM} = N_{TM0}/N_{TE0}$.

Oblique resonant excitation of a dielectric strip





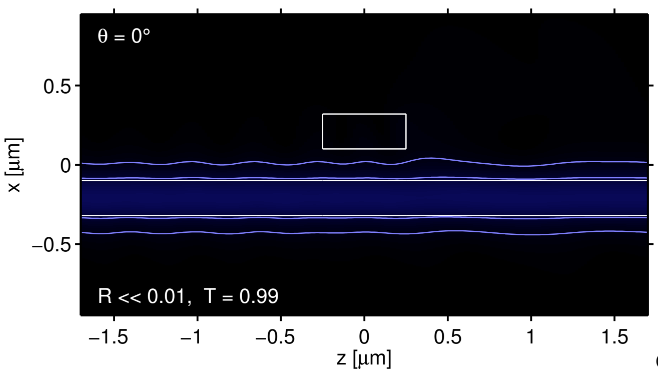
$n_g = 3.45$, $n_b = 1.45$,
$d = 0.22\,\mu m$, $\lambda = 1.55\,\mu m$, in: TE_0,
$\theta_b = 30.9°$, $\theta_{TM} = 46.3°$,

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

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

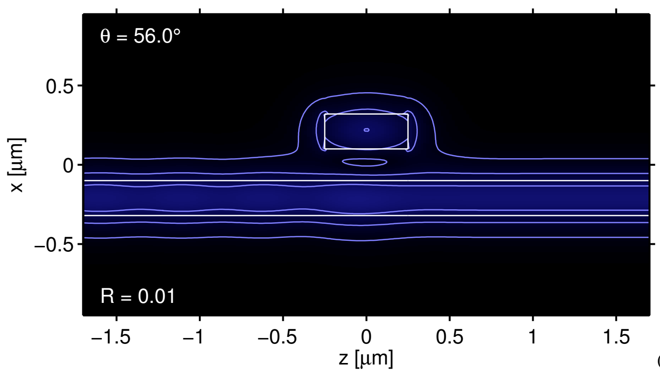
↪ Resonant interaction with the waves in the slab expected at $\theta \approx \theta_m$,
where $k_y = kN_{in}\sin\theta \approx kN_m$, $\sin\theta_m = N_m/N_{in}$.

Strip resonator, fields



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

Strip resonator, fields



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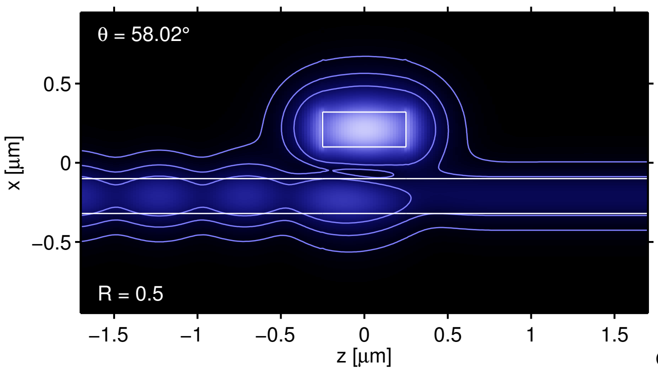

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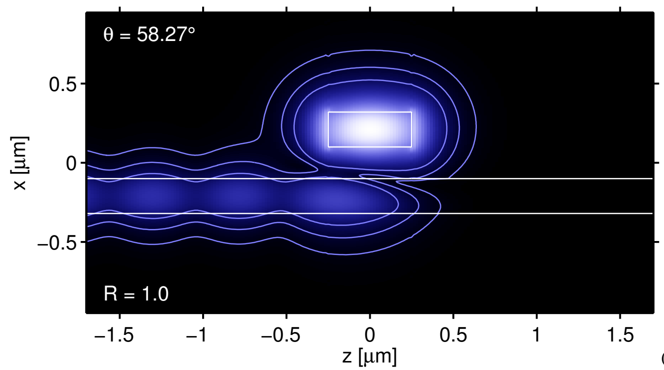
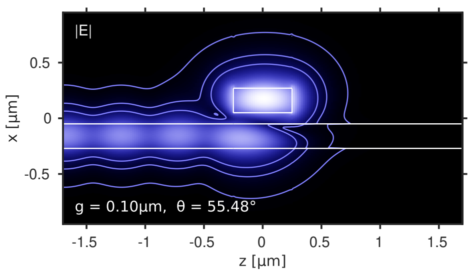
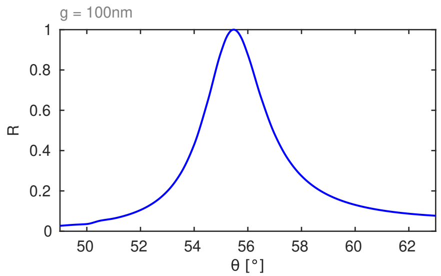
Strip resonator, fields



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

Oblique resonant excitation of a dielectric strip





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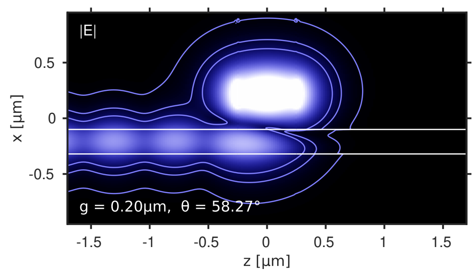

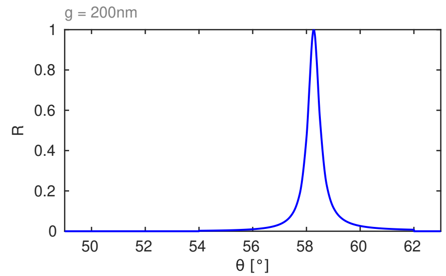

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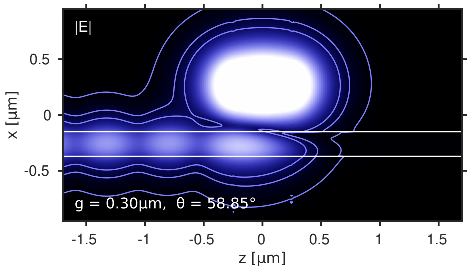

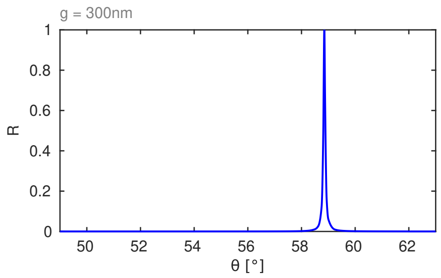

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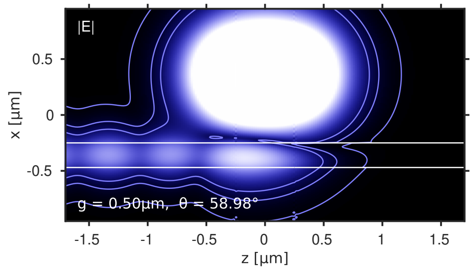

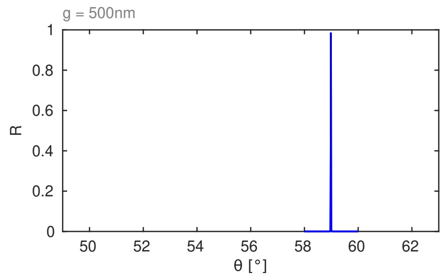

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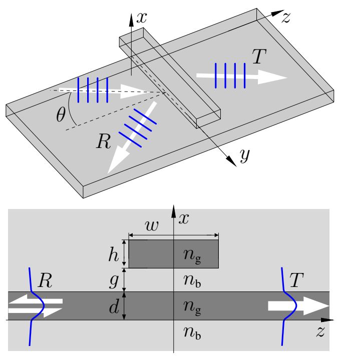

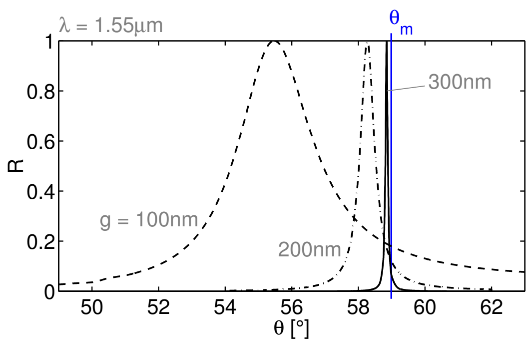

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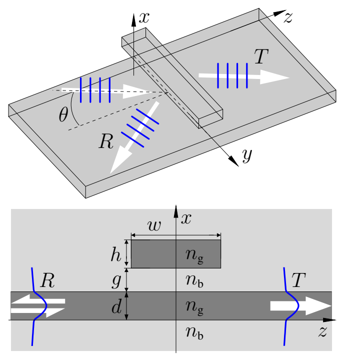
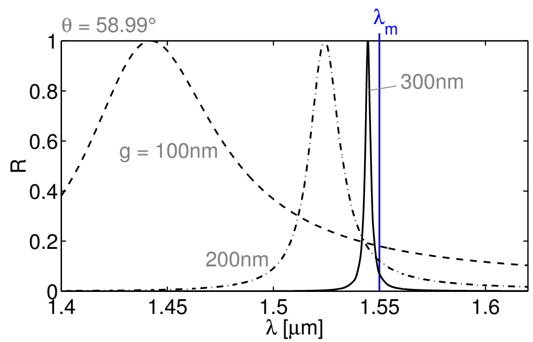
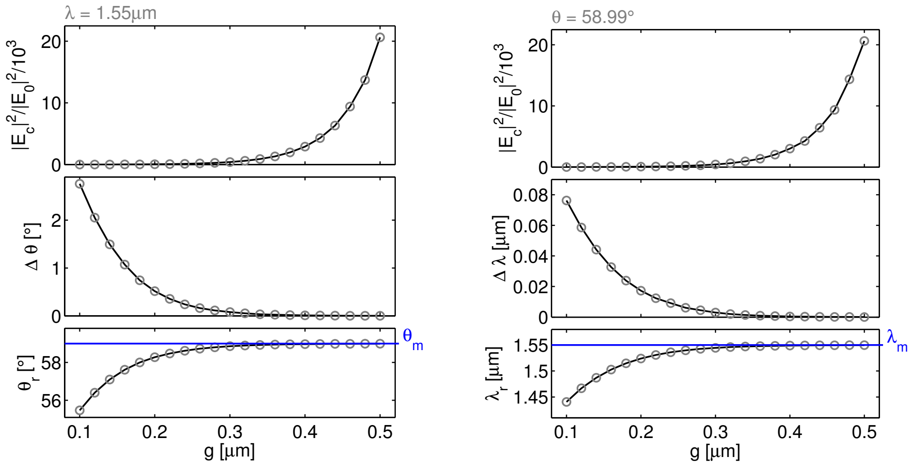
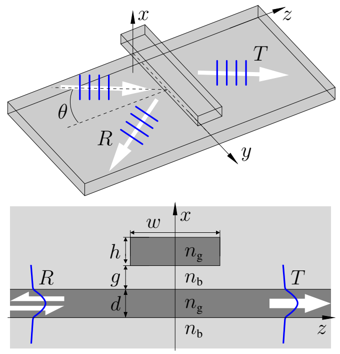


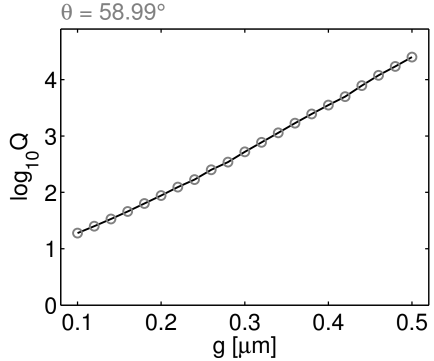


Strip resonator, resonance properties



Strip resonator, resonance properties





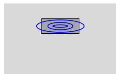
$$Q = \lambda_r/\Delta\lambda.$$

Strip resonator, formation of resonances

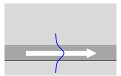
(fixed $\theta = \theta_m$, variable λ, ω)

Relevant states:

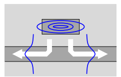
- the bound state Ψ_m of the isolated cavity (large g), eigenfrequency $\omega_m = 2\pi c/\lambda_m \in \mathbb{R}$,



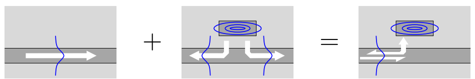
- a continuum of guided waves Ψ_s in the isolated slab (large g), frequencies $\omega \in [\omega_0, \omega_1]$, where $\omega_0 < \omega_m < \omega_1$,



- the leaky eigenstate Ψ_c of the composite system (finite g), eigenfrequency $\omega_c \in \mathbb{C}$, $\Psi_c \to \Psi_m$ with $\omega_c \to \omega_m$ at large g,

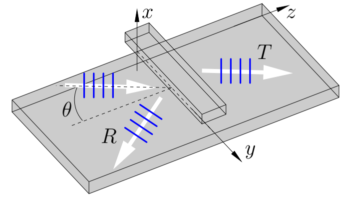


- the resonant transmission state Ψ_t (finite g), a superposition of Ψ_c and Ψ_s.



Concluding remarks

Oblique semi-guided excitation of a dielectric strip:



- an open dielectric resonator with unlimited Q,
- exceptionally simple,
- a system that supports a bound state and a continuum of waves in a frequency range that covers the real eigenfrequency of the bound state: "Bound state Coupled to a Continuum" (BCC).

(. . . BIC ?)