Lossless operation of high-contrast integrated optical waveguide gratings

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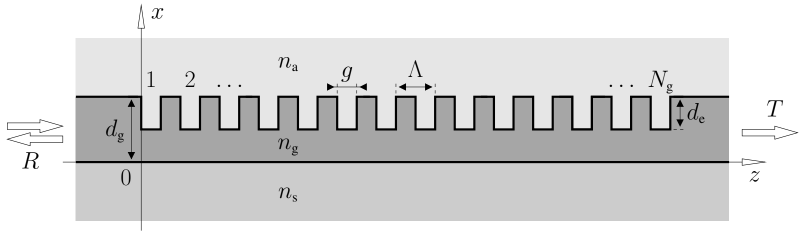
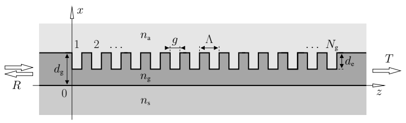
COST 268 benchmark, waveguide Bragg grating, 2-D

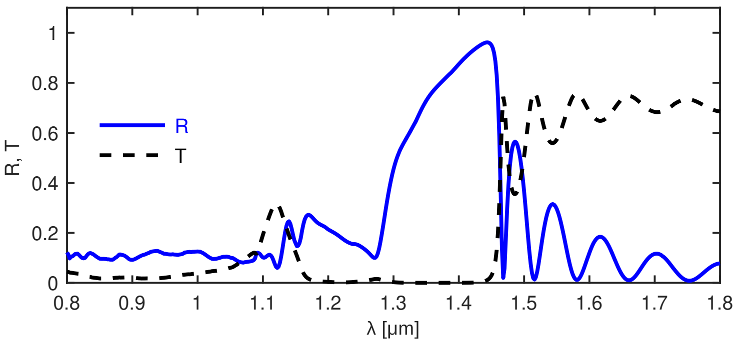


$n_s \approx 1.45$, $n_g \approx 1.99$, $n_a = 1.0$, $d_g = 0.5\,\mu m$, $d_e = 0.375\,\mu m$, $\Lambda = 0.430\,\mu m$, $g = \Lambda/2$, $N_g = 20$,
in: TE, $\lambda \in [0.8, 1.8]\,\mu m$.

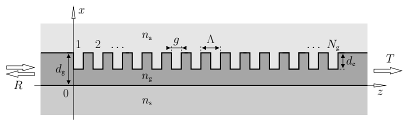
J. Čtyroký, S. Helfert, R. Pregla, P. Bienstman, R. Baets, R. de Ridder, R. Stoffer, G. Klaase, J. Petráček, P. Lalanne, J.-P. Hugonin, and R. M. De La Rue,
Bragg waveguide grating as a 1D photonic band gap structure: COST 268 modelling task,
Optical and Quantum Electronics **34**(5/6), 455–470, 2002.

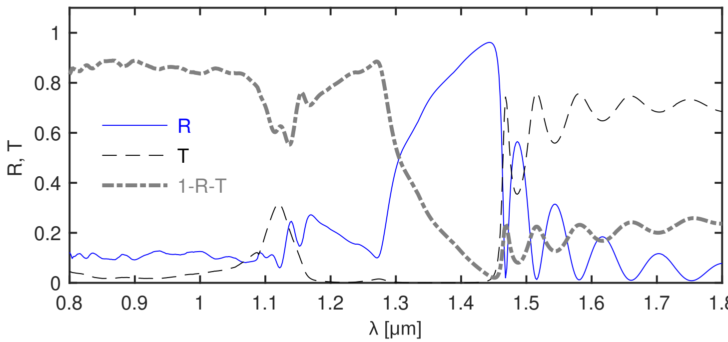
COST 268 benchmark, waveguide Bragg grating, 2-D





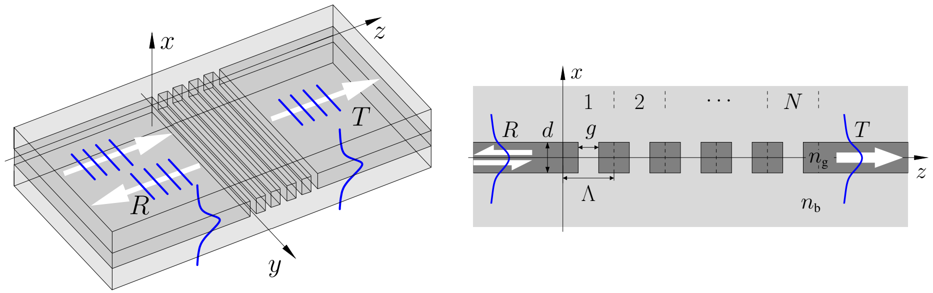
COST 268 benchmark, waveguide Bragg grating, 2-D





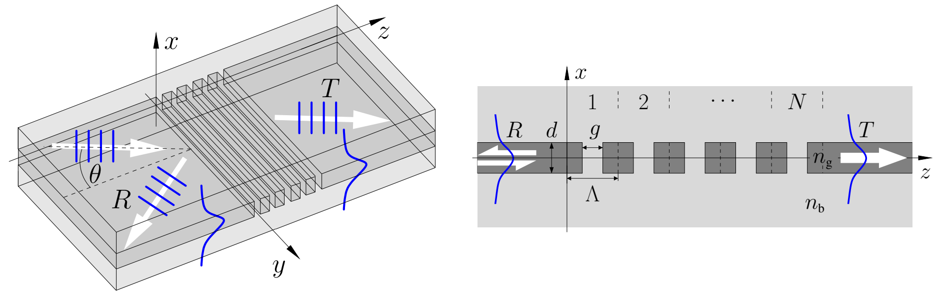
Simple waveguide Bragg grating

(2-D)



Simple waveguide Bragg grating

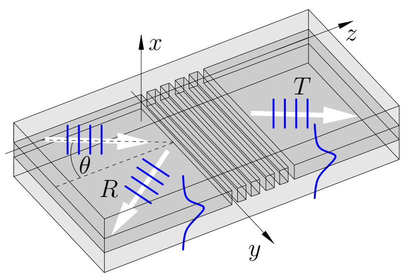
(2.5-D)



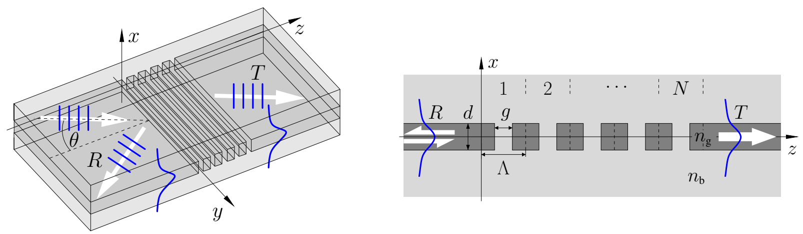
Lossless operation of high-contrast integrated optical waveguide gratings

Overview

- Oblique incidence of semi-guided waves
- Band structure analysis
- Symmetric high-contrast grating
- Apodization
- Reduced reflector strength
- Narrow-band Fabry-Perot filter

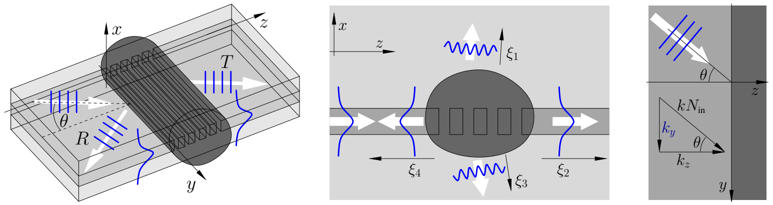


High-contrast waveguide Bragg gratings



$n_b = 1.45$ (SiO_2), $n_f = 3.45$ (Si), $d = 0.22$ µm, variable Λ, g, N; TE-excitation at $\theta = 45^\circ$ for $\lambda \in [0.8, 2.2]$ µm.

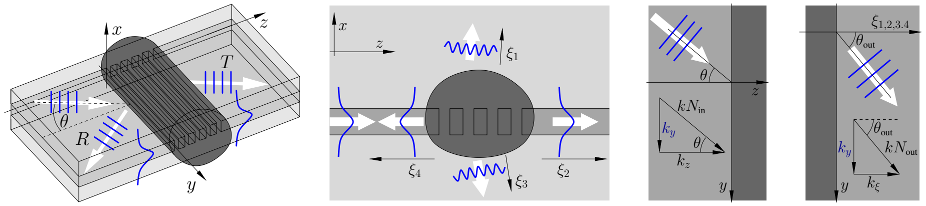
Semi guided waves at oblique angles of incidence



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

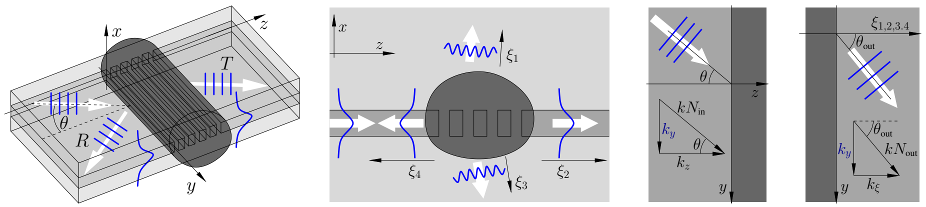
- Incoming slab mode $\{N_{\rm in}; \boldsymbol{\Psi}_{\rm in}\}$, $(\boldsymbol{E},\boldsymbol{H}) \sim \boldsymbol{\Psi}_{\rm in}(x)\,\mathrm{e}^{-\mathrm{i}(k_y y + k_z z)}$,
  incidence angle θ, $k^2N_{\rm in}^2 = k_y^2 + k_z^2$, $k_y = kN_{\rm in}\sin\theta$.
- y-homogeneous problem: $(\boldsymbol{E},\boldsymbol{H})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

Semi guided waves at oblique angles of incidence



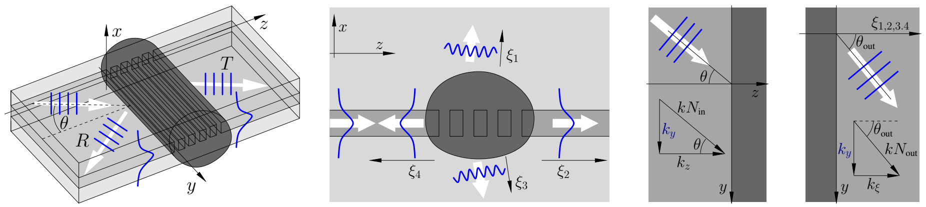
- Outgoing wave $\{N_{\rm out}; \boldsymbol{\Psi}_{\rm out}\}$, $(\boldsymbol{E},\boldsymbol{H}) \sim \boldsymbol{\Psi}_{\rm out}(\,.\,)\,\mathrm{e}^{-\mathrm{i}(k_y y + k_\xi \xi)}$,
  $k^2N_{\rm out}^2 = k_y^2 + k_\xi^2$, $k_y = kN_{\rm in}\sin\theta$.
- $k^2N_{\rm out}^2 > k_y^2$: $k_\xi = kN_{\rm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

Semi guided waves at oblique angles of incidence



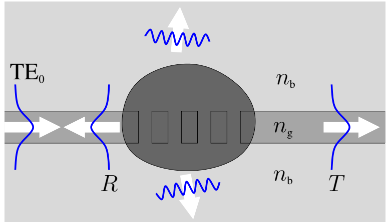
- Outgoing wave $\{N_{\rm out}; \boldsymbol{\Psi}_{\rm out}\}$, $(\boldsymbol{E},\boldsymbol{H}) \sim \boldsymbol{\Psi}_{\rm out}(\,.\,)\,\mathrm{e}^{-\mathrm{i}(k_y y + k_\xi \xi)}$,
  $k^2N_{\rm out}^2 = k_y^2 + k_\xi^2$, $k_y = kN_{\rm in}\sin\theta$.
- $k^2N_{\rm out}^2 < k_y^2$: $k_\xi = -\mathrm{i}\sqrt{k_y^2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

Semi guided waves at oblique angles of incidence



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

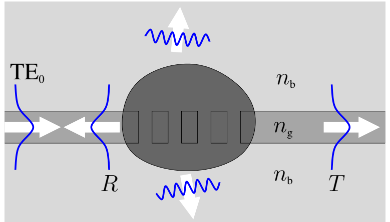
Critical angles



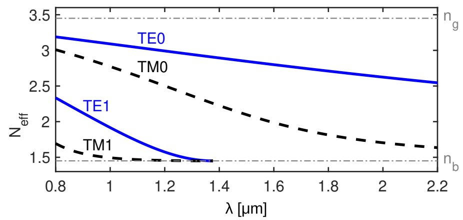
$n_g > n_b$,
$N_{TE0} > N_{TM0} > N_{TE1} > N_{TM1} > n_b$,
in: TE$_0$.

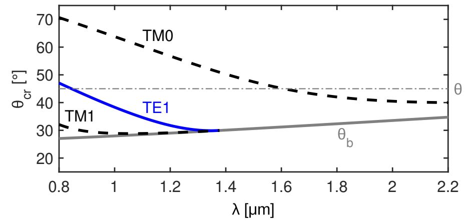
- Outgoing mode $\in \{TM_0, TE_1, TM_1\}$ with effective mode indices $N_{out} < N_{TE0}$
  $\rightsquigarrow$ $R_{out} = T_{out} = 0$, for $\theta > \theta_{cr}$, $\sin\theta_{cr} = N_{out}/N_{TE0}$.
- Propagation in the substrate and cladding relates to effective indices $N_{out} \leq n_b$
  $\rightsquigarrow$ $R_{TE0,1} + R_{TM0,1} + T_{TE0,1} + T_{TM0,1} = 1$ for $\theta > \theta_b$, $\sin\theta_b = n_b/N_{TE0}$.

Critical angles

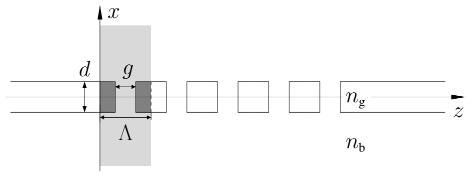


$n_g > n_b$,
$N_{TE0} > N_{TM0} > N_{TE1} > N_{TM1} > n_b$,
in: TE$_0$.





Band structure

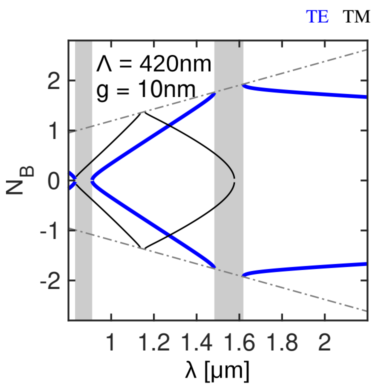


$$(\boldsymbol{E}, \boldsymbol{H})(x, y, z) = \boldsymbol{\Psi}(x, z)\, e^{-ik_y y}\, e^{-i\beta z},$$

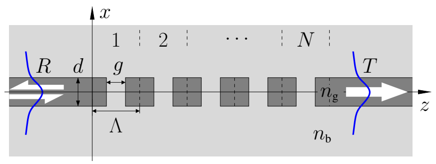
$\sim e^{i\omega t}$, $\omega = kc = 2\pi c/\lambda$,
$\beta = kN_B$, $\boldsymbol{\Psi}(x, z+\Lambda) = \boldsymbol{\Psi}(x, z)$,

$(\boldsymbol{E}, \boldsymbol{H})(x, y, \Lambda) = (\boldsymbol{E}, \boldsymbol{H})(x, y, 0)\, e^{-i\beta\Lambda}$,
$\partial_z(\boldsymbol{E}, \boldsymbol{H})(x, y, \Lambda) = \partial_z(\boldsymbol{E}, \boldsymbol{H})(x, y, 0)\, e^{-i\beta\Lambda}$,

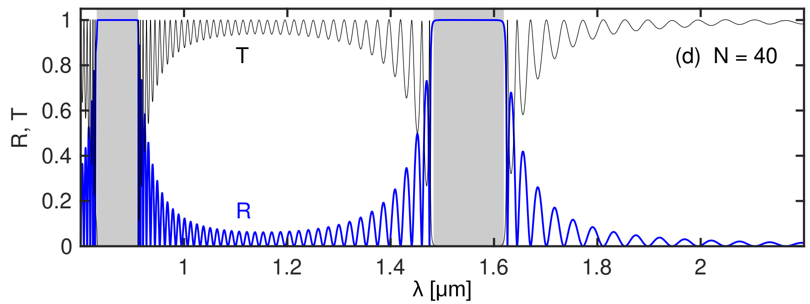
$\beta \in [-\pi/\Lambda, \pi/\Lambda]$, $N_B \in [-\lambda/(2\Lambda), \lambda/(2\Lambda)]$.



Spectra

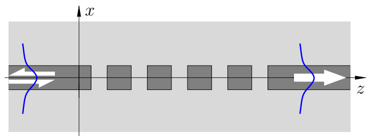


$\Lambda = 420$ nm, $g = 10$ nm,
$\theta = 45°$, in: TE$_0$,
bandgap at $\approx$1.55 µm, width 136 nm.



Symmetry

Mirror symmetry $x \leftrightarrow -x$



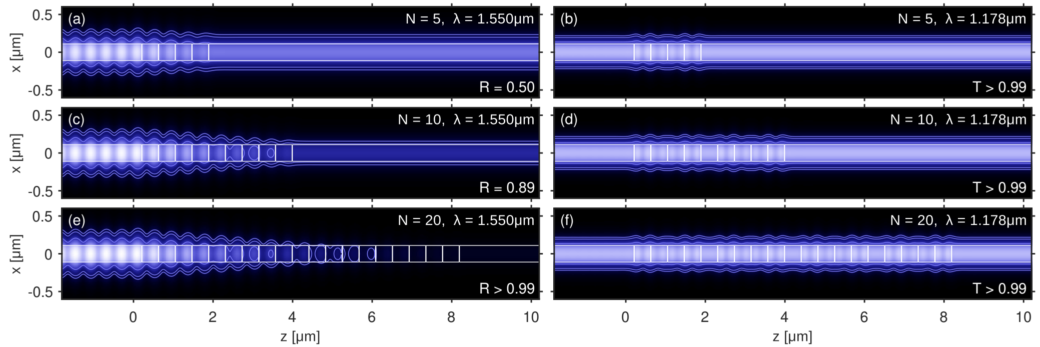
	E_x	E_y	E_z	H_x	H_y	H_z	
TE_0	−	+	+	+	−	−	$PMC_{x=0}$
TM_0	+	−	−	−	+	+	$PEC_{x=0}$
TE_1	+	−	−	−	+	+	$PEC_{x=0}$
TM_1	−	+	+	+	−	−	$PMC_{x=0}$

- Symmetry of the incoming TE_0-field extends to the full solution.

↪ Excitation of TM_0 and TE_1-modes is suppressed.

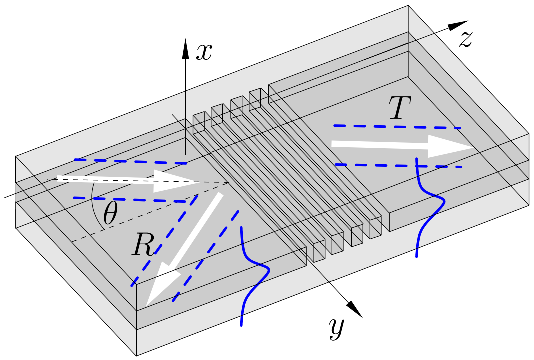
Fields

(electromagnetic energy density)

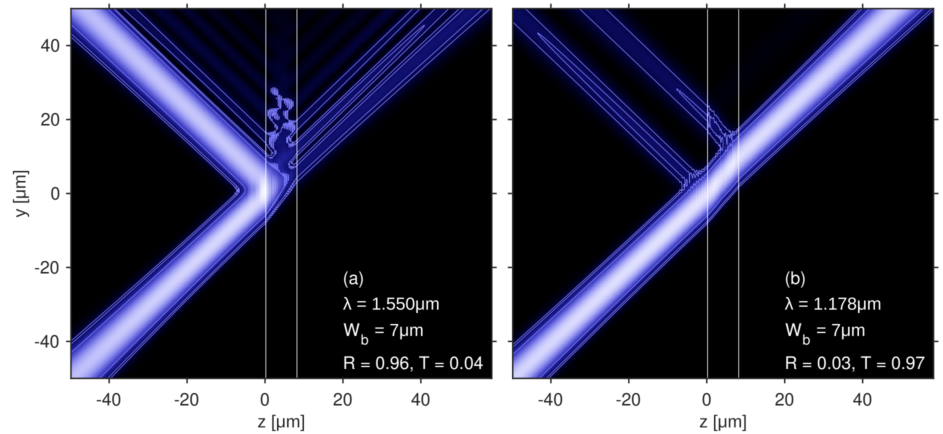


Laterally limited input

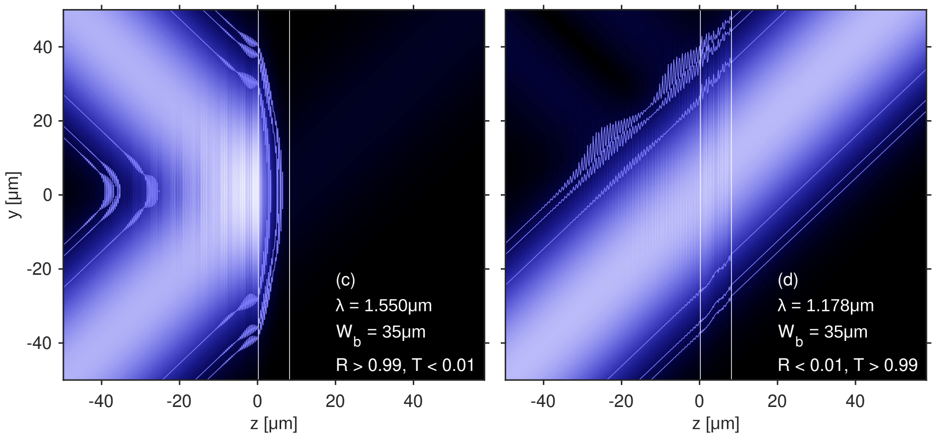
(3-D) $\partial_y \epsilon = 0, \ (\boldsymbol{E}, \boldsymbol{H}) = \int (\ . \ ) \, \mathrm{e}^{-\mathrm{i} k_y y} \, \mathrm{d}k_y$



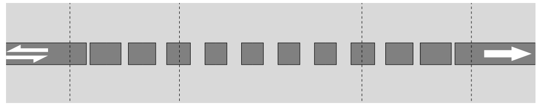
Incoming semi-guided beams



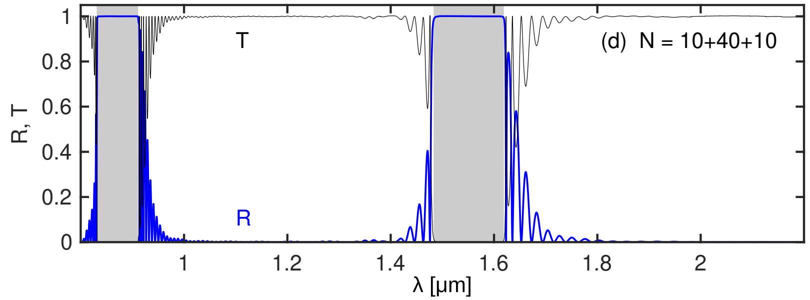
Incoming semi-guided beams



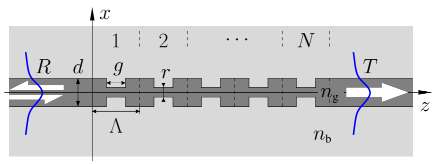
Apodized gratings



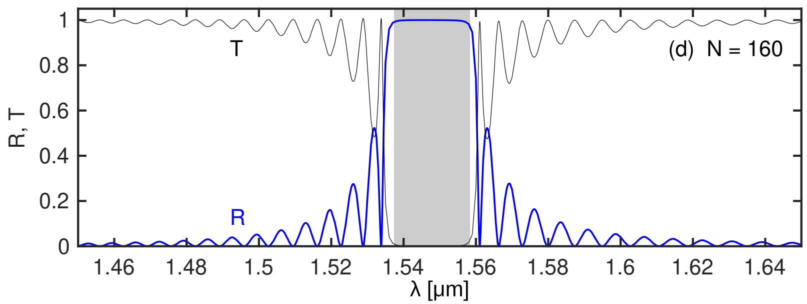
$\Lambda = 420\,\text{nm}$, $g = 10\,\text{nm}$,
$\theta = 45°$, in: TE_0,
bandgap at $\approx 1.55\,\mu\text{m}$, width $136\,\text{nm}$.



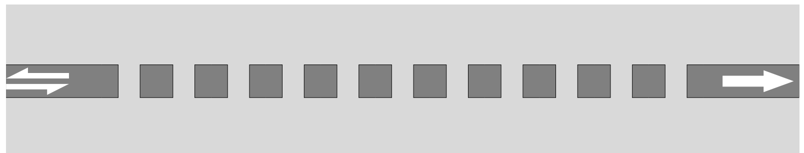
Reduced reflector strength



$\Lambda = 411\,\text{nm}$, $g = 110\,\text{nm}$, $r = 160\,\text{nm}$,
$\theta = 45°$, in: TE_0,
bandgap at $\approx 1.55\,\mu\text{m}$, width $20\,\text{nm}$.



Defect gratings



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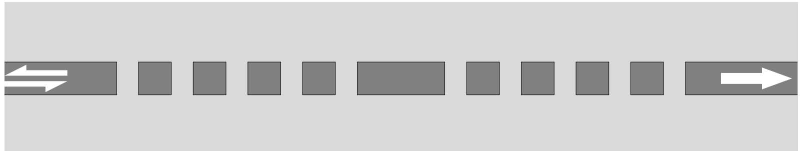

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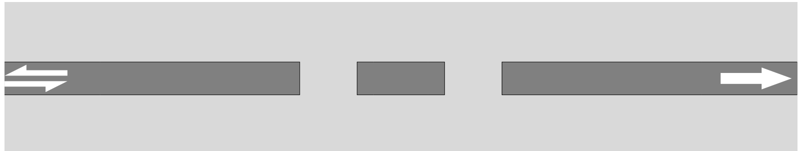
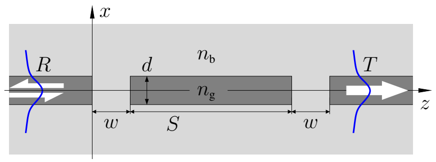
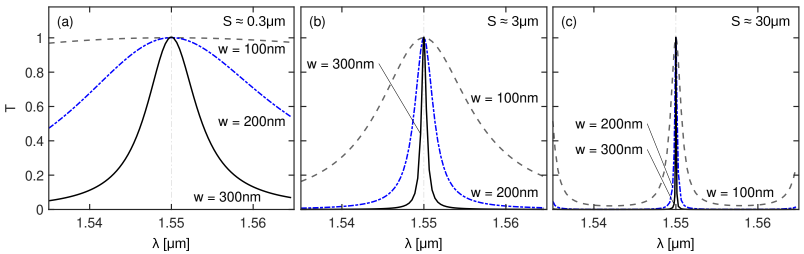


Narrow-band Fabry-Perot filter



$S/$ µm	3.439	3.444	30.231	30.236
$w/$ nm	200	300	200	300
$2\delta\lambda/$ nm	2.7	0.7	0.3	0.08
Q	$5 \cdot 10^2$	$2 \cdot 10^3$	$5 \cdot 10^3$	$2 \cdot 10^4$



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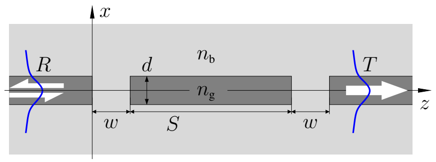

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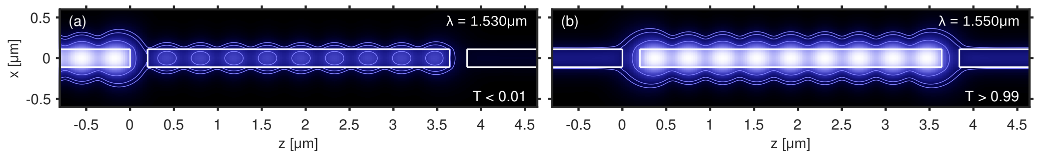

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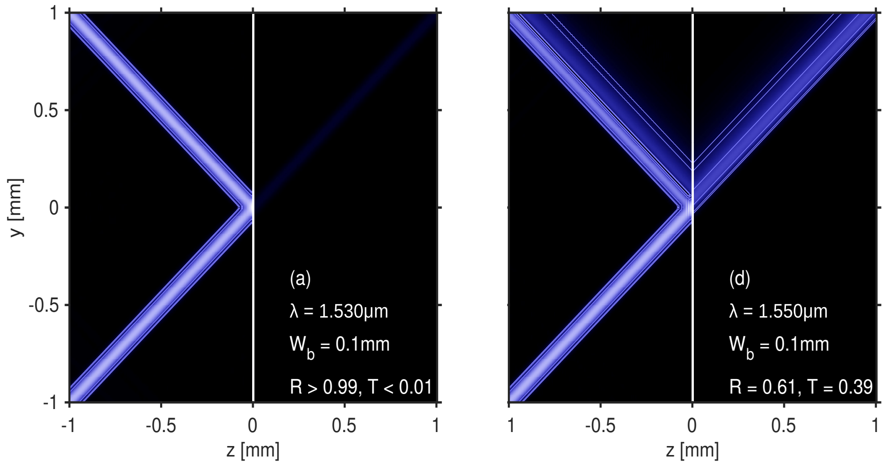

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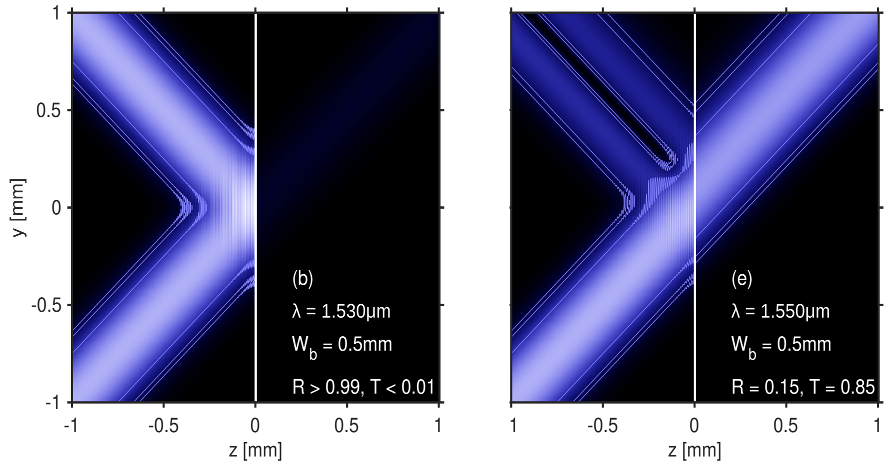

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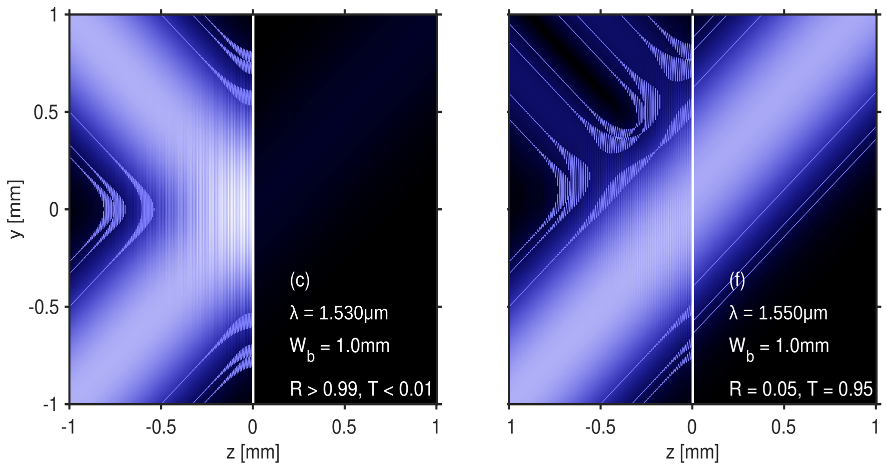

Concluding remarks

Lossless (. . .) high-contrast integrated optical waveguide gratings

- realized with oblique incidence of semi-guided waves,
- grating symmetry and critical angles lead to true single-mode operation,
- spectral filters with reasonable flat-top response, apodization possible,
- widths of reflection bands / transmission peaks span three orders of magnitude.

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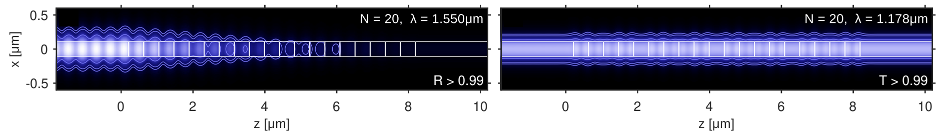

Funding: Ministry of Culture and Science of the State of North Rhine-Westphalia, project *Photonic Quantum Computing* (PhoQC), Paderborn University.

Ministry of Culture and Science of the State of North Rhine-Westphalia