

## Simple beam splitters for semi-guided waves in integrated silicon photonics

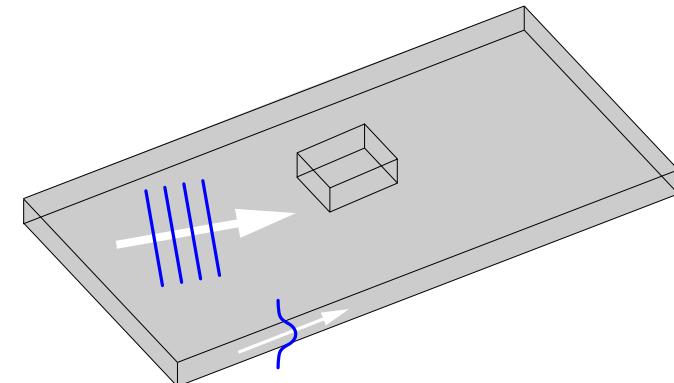
Manfred Hammer\*, Lena Ebers, Jens Förstner

Paderborn University  
Theoretical Electrical Engineering  
Paderborn, Germany

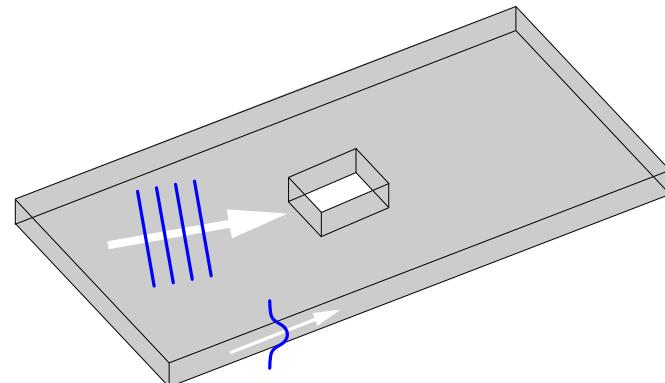
15th Annual Meeting Photonic Devices, Zuse Institute Berlin, Berlin, Germany, March 29–31, 2023

\*Paderborn University, Theoretical Electrical Engineering  
Warburger Straße 100, 33098 Paderborn, Germany  
Phone: +49(0)5251/60-3560  
E-mail: manfred.hammer@uni-paderborn.de

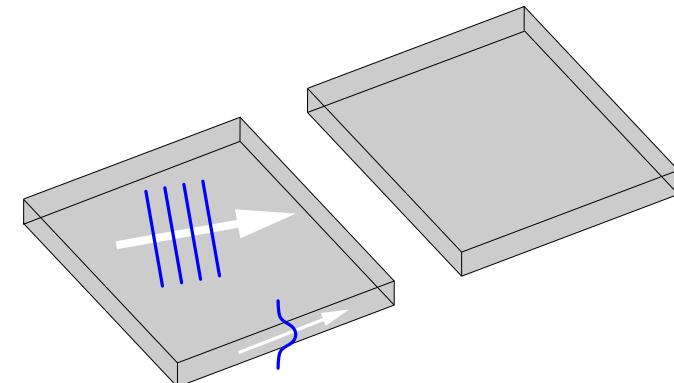
### Scatterers for semi-guided waves



### Scatterers for semi-guided waves



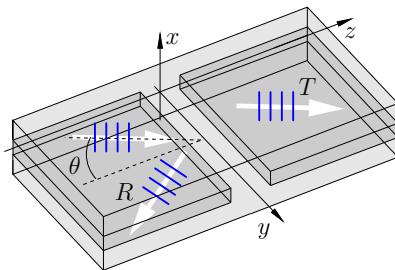
### Scatterers for semi-guided waves



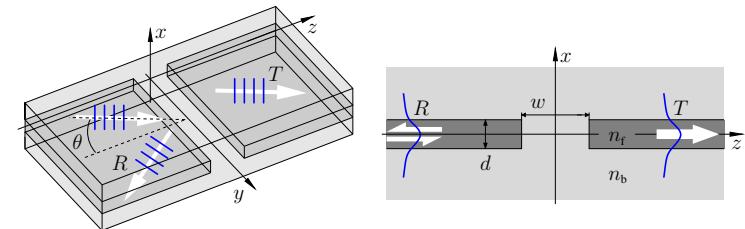
## Simple beam splitters for semi-guided waves in integrated silicon photonics

### Overview

- Oblique incidence of semi-guided waves
- Facets, reflectance
- Power dividers
- Bundles of semi-guided waves
- Cascaded devices

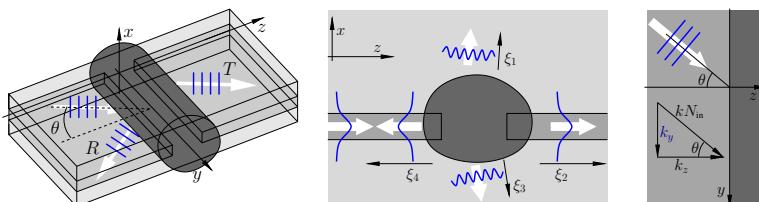


## High-contrast slabs



$n_b = 1.45$  (SiO<sub>2</sub>),  $n_f = 3.45$  (Si),  $d = 0.22 \mu\text{m}$ , variable  $w$ ; TE- / TM-excitation at  $\lambda = 1.55 \mu\text{m}$ , varying  $\theta$ .

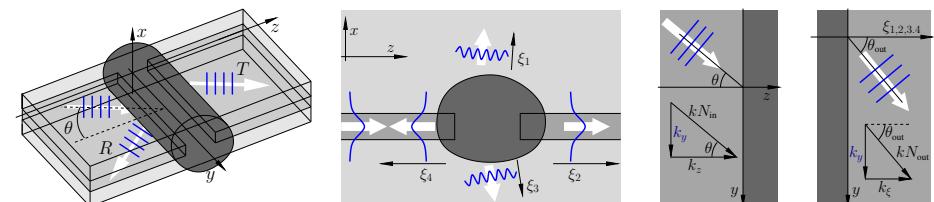
## Semi guided waves at oblique angles of incidence



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

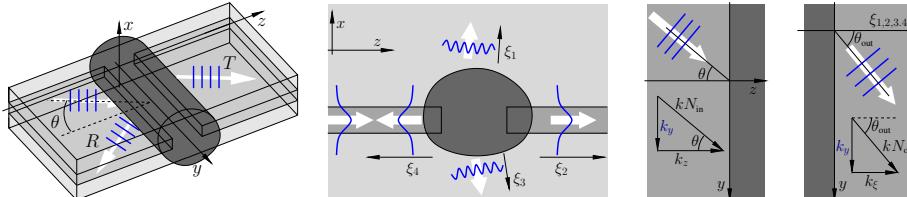
- Incoming slab mode  $\{N_{\text{in}}; \Psi_{\text{in}}\}$ ,  $(E, H) \sim \Psi_{\text{in}}(x) e^{-i(k_y y + k_z z)}$ , incidence angle  $\theta$ ,  $k^2 N_{\text{in}}^2 = k_y^2 + k_z^2$ ,  $k_y = k N_{\text{in}} \sin \theta$ .
- y-homogeneous problem:  $(E, H) \sim e^{-ik_y y}$  everywhere.

## Semi guided waves at oblique angles of incidence



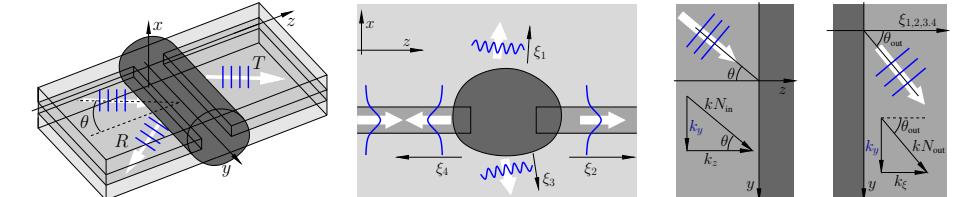
- Outgoing wave  $\{N_{\text{out}}; \Psi_{\text{out}}\}$ ,  $(E, H) \sim \Psi_{\text{out}}(\cdot) e^{-i(k_y y + k_\xi \xi)}$ ,  $k^2 N_{\text{out}}^2 = k_y^2 + k_\xi^2$ ,  $k_\xi = k N_{\text{in}} \sin \theta$ .
- $k^2 N_{\text{out}}^2 > k_y^2$ :  $k_\xi = k N_{\text{out}} \cos \theta_{\text{out}}$ ,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

## Semi guided waves at oblique angles of incidence



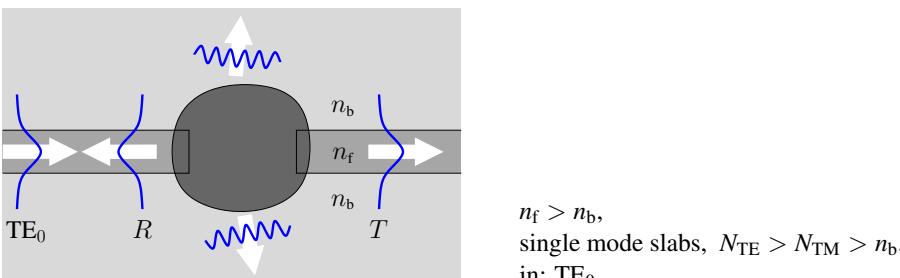
- Outgoing wave  $\{N_{\text{out}}; \Psi_{\text{out}}\}$ ,  $(E, H) \sim \Psi_{\text{out}}(\cdot) e^{-i(k_y y + k_\xi \xi)}$ ,  
 $k^2 N_{\text{out}}^2 = k_y^2 + k_\xi^2$ ,  $k_y = kN_{\text{in}} \sin \theta$ .
- $k^2 N_{\text{out}}^2 < k_y^2$ :  $k_\xi = -i\sqrt{k_y^2 - k^2 N_{\text{out}}^2}$ ,  $\xi$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

## Semi guided waves at oblique angles of incidence



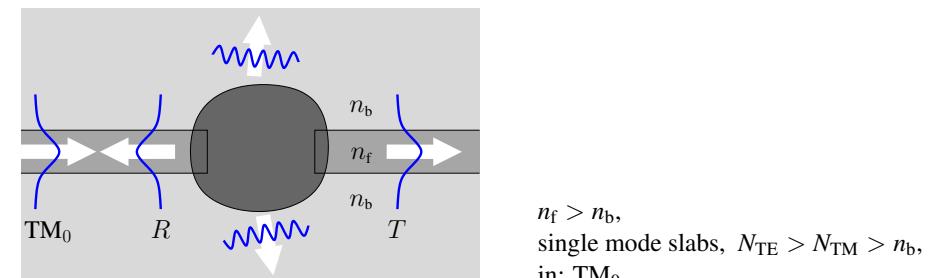
- Outgoing wave  $\{N_{\text{out}}; \Psi_{\text{out}}\}$ ,  $(E, H) \sim \Psi_{\text{out}}(\cdot) e^{-i(k_y y + k_\xi \xi)}$ ,  
 $k^2 N_{\text{out}}^2 = k_y^2 + k_\xi^2$ ,  $k_y = kN_{\text{in}} \sin \theta$ .
- Scan over  $\theta$ :  
change from  $\xi$ -propagating to  $\xi$ -evanescent if  $k^2 N_{\text{out}}^2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

## Critical angles



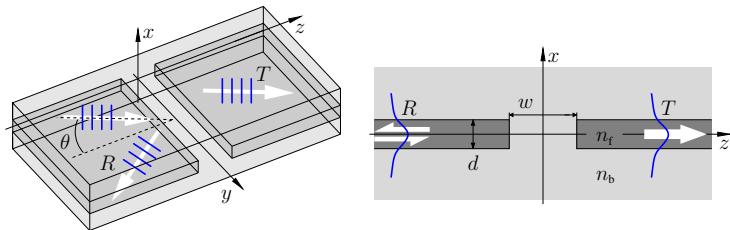
- Propagation in the substrate and cladding relates to effective indices  $N_{\text{out}} \leq n_b$   
→  $R_{\text{TE}} + R_{\text{TM}} + T_{\text{TE}} + T_{\text{TM}} = 1$  for  $\theta > \theta_b$ ,  $\sin \theta_b = n_b/N_{\text{TE}}$ .
- TM polarized waves relate to effective mode indices  $N_{\text{out}} \leq N_{\text{TM}}$   
→  $R_{\text{TM}} = T_{\text{TM}} = 0$ ,  $R_{\text{TE}} + T_{\text{TE}} = 1$  for  $\theta > \theta_{\text{TM}}$ ,  $\sin \theta_{\text{TM}} = N_{\text{TM}}/N_{\text{TE}}$ .

## Critical angles



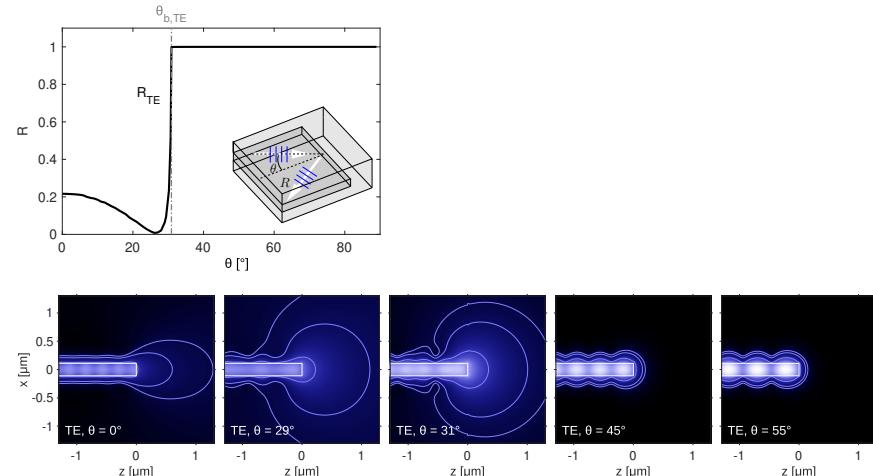
- Propagation in the substrate and cladding relates to effective indices  $N_{\text{out}} \leq n_b$   
→  $R_{\text{TE}} + R_{\text{TM}} + T_{\text{TE}} + T_{\text{TM}} = 1$  for  $\theta > \theta_b$ ,  $\sin \theta_b = n_b/N_{\text{TM}}$ .

## High-contrast slabs

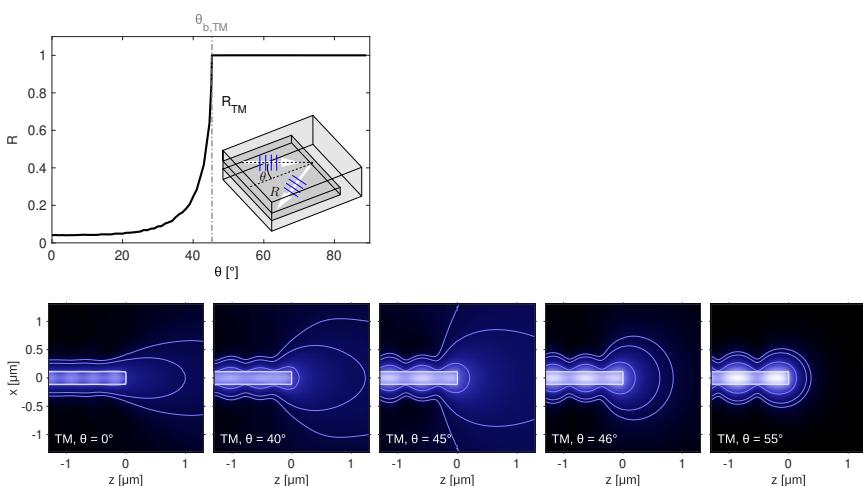


$n_b = 1.45$  (SiO<sub>2</sub>),  $n_f = 3.45$  (Si),  $d = 0.22 \mu\text{m}$ , variable  $w$ ; TE- / TM-excitation at  $\lambda = 1.55 \mu\text{m}$ , varying  $\theta$ .  
TE input:  $\theta_b = 30.91^\circ$ ,  $\theta_{TM} = 46.27^\circ$ ; TM input:  $\theta_b = 45.31^\circ$ .

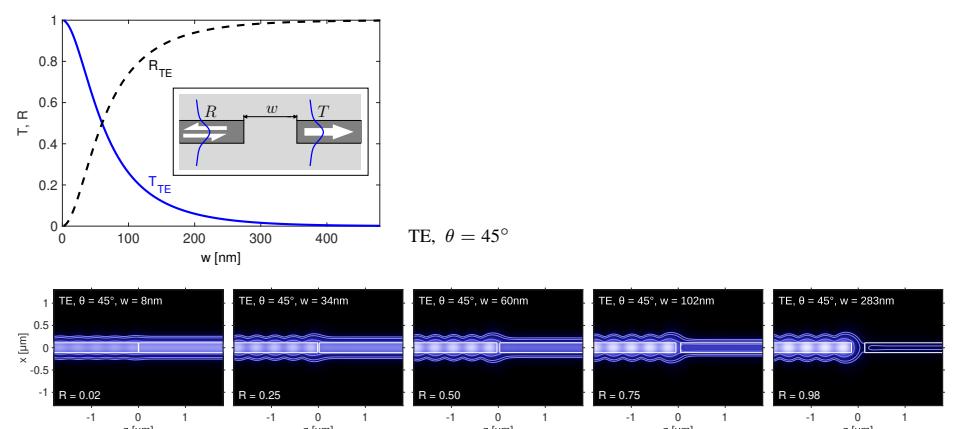
## Facet



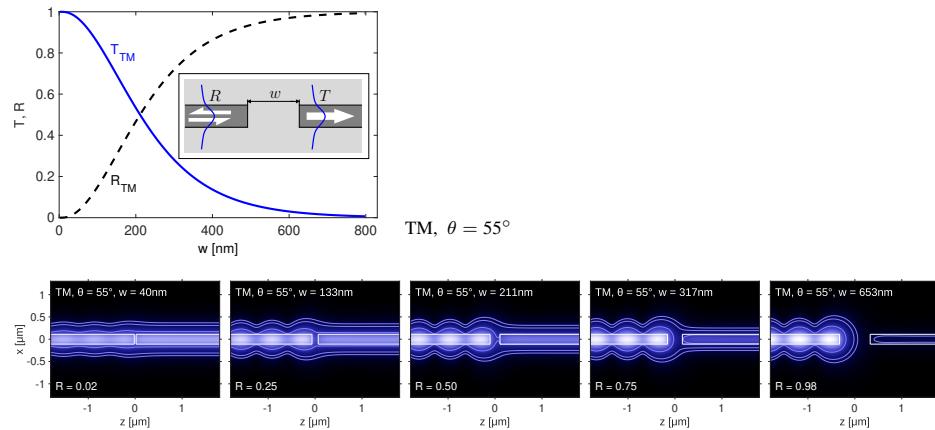
## Facet



## Power dividers

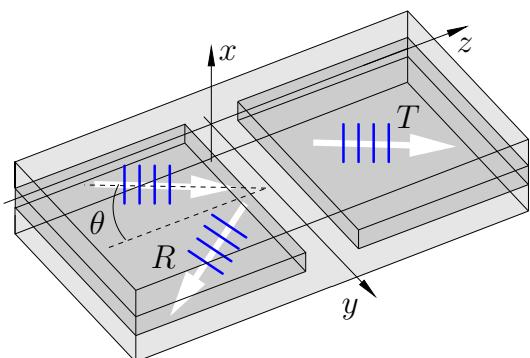


**Power dividers**

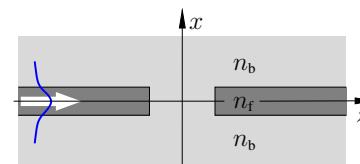


### **Laterally limited input**

$$(2.5\text{-D}) \quad \partial_y \epsilon = 0, \quad (\mathbf{E}, \mathbf{H}) \sim \exp(-ik_y y), \quad k_y \sim \sin \theta$$



Symmetry

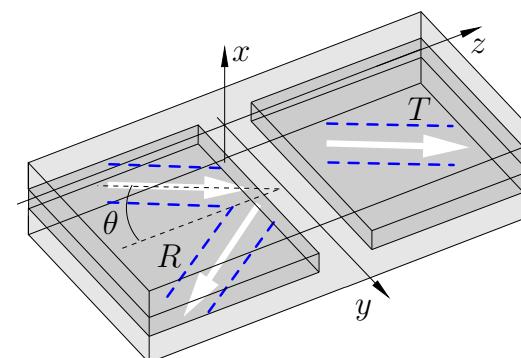


Mirror symmetry $x \leftrightarrow -x$						
In	$E_x$	$E_y$	$E_z$	$H_x$	$H_y$	$H_z$
$\text{TE}_0$	—	+	+	+	—	—
$\text{TM}_0$	+	—	—	—	+	+

- Symmetry of the incoming field extends to the full solution.
  - $\theta > \theta_b$ : Power carried by TE<sub>0</sub> and TM<sub>0</sub> modes only.
  - ↪ Polarization conversion TE  $\leftrightarrow$  TM is forbidden.

### **Laterally limited input**

$$(3-D) \quad \partial_y \epsilon = 0, \quad (\mathbf{E}, \mathbf{H}) = \int ( \cdot ) \exp(-ik_y y) dk_y$$



A set of small, light-gray navigation icons typically found in presentation software like Beamer. They include symbols for back, forward, search, and other document-related functions.

11

## Gaussian bundles of semi-guided waves

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

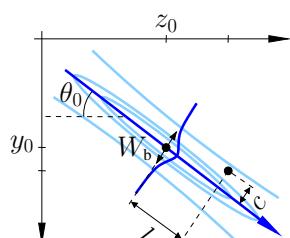
$$(\mathbf{E}, \mathbf{H})(x, y, z) = A \int e^{-\frac{(k_y - k_{y0})^2}{w_k^2}} \left( \Psi_{in}(k_y; x) e^{-ik_z(k_y)(z - z_0)} + \rho(k_y; x, z) \right) e^{-ik_y(y - y_0)} dk_y$$

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

## Gaussian bundles of semi-guided waves

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

$$(\mathbf{E}, \mathbf{H})_{in}(x, c, l) \sim e^{-\frac{c^2}{(W_b/2)^2}} \Psi_{in}(k_{y0}; x) e^{-ikN_{in}l}$$

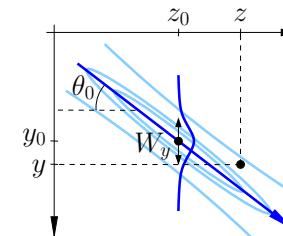


Focus at  $(y_0, z_0)$ ,  
primary angle of incidence  $\theta_0$ ,  
 $k_{y0} = kN_{in} \sin \theta_0$ ,  
 $k_{z0} = kN_{in} \cos \theta_0$ ,  
width  $W_b$  (full, along y, 1/e, field, at focus),  
 $W_y = 4/w_k$ ,  $W_b = W_y \cos \theta_0$ .

## Gaussian bundles of semi-guided waves

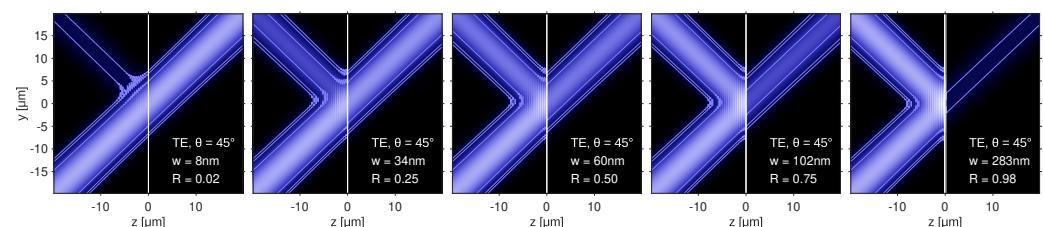
- Superimpose 2-D solutions for a range of  $k_y$  / a range of  $\theta$ , such that the input field resembles an in-plane confined beam.
- Incoming wave, “small”  $w_k$ :

$$(\mathbf{E}, \mathbf{H})_{in}(x, y, z) \sim e^{-\frac{\left((y - y_0) - \frac{k_{y0}}{k_{z0}}(z - z_0)\right)^2}{(W_y/2)^2}} \Psi_{in}(k_{y0}; x) e^{-i(k_{y0}(y - y_0) + k_{z0}(z - z_0))}$$



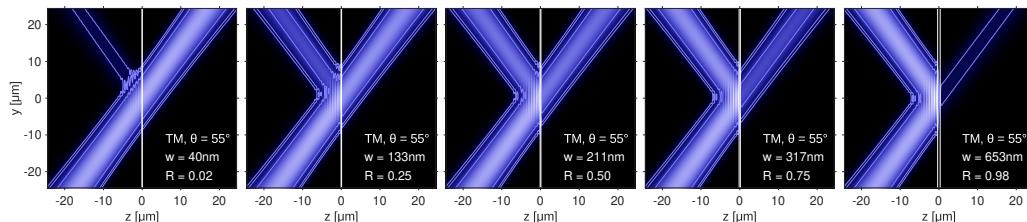
Focus at  $(y_0, z_0)$ ,  
primary angle of incidence  $\theta_0$ ,  
 $k_{y0} = kN_{in} \sin \theta_0$ ,  
 $k_{z0} = kN_{in} \cos \theta_0$ ,  
width  $W_y$  (full, along y, 1/e, field, at focus),  
 $W_y = 4/w_k$ .

## Power dividers, excitation by semi-guided beams

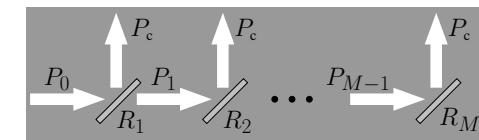


TE,  $\theta = 45^\circ$ ,  $W_b = 8 \mu\text{m}$ ,  $R_{TE} + T_{TE} = 1$

## Power dividers, excitation by semi-guided beams

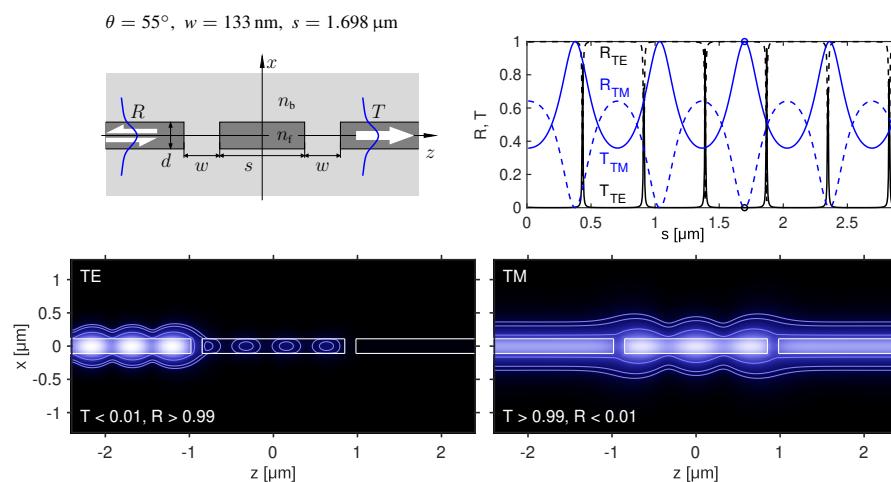


## $1 \times M$ power divider

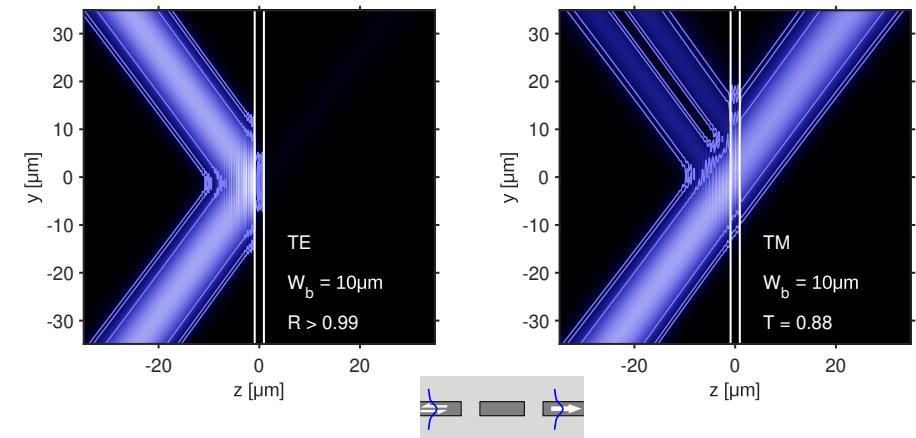


$$R_j = 1/(M - j + 1) \quad \rightsquigarrow \quad P_c = P_0/M$$

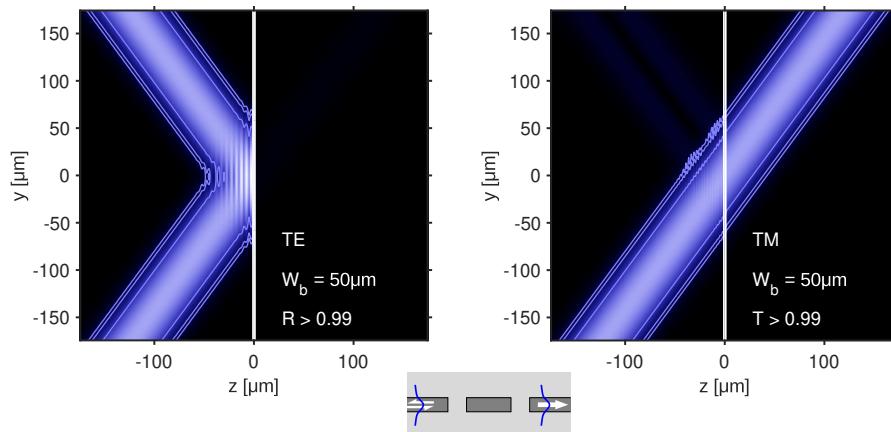
## Polarization beam splitter



## Polarization beam splitter



## Polarization beam splitter

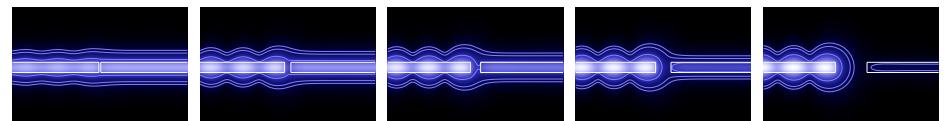


## **Concluding remarks**

## Simple beam splitters for semi-guided waves in integrated silicon photonics

- Trenches in a high-contrast slab act as simple power dividers for semi-guided waves,
  - working principle: frustrated total internal reflection,
  - lossless (...), easily configurable for splitting ratios  $\in [0, 1]$ ,
  - cascading: dividers with multiple outlets, polarization splitter.

OSA Continuum 4(12), 3081–3095 (2021)



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

