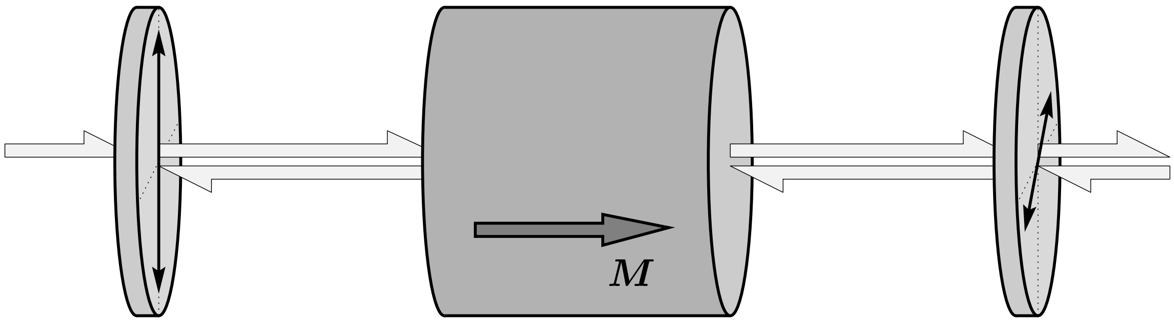
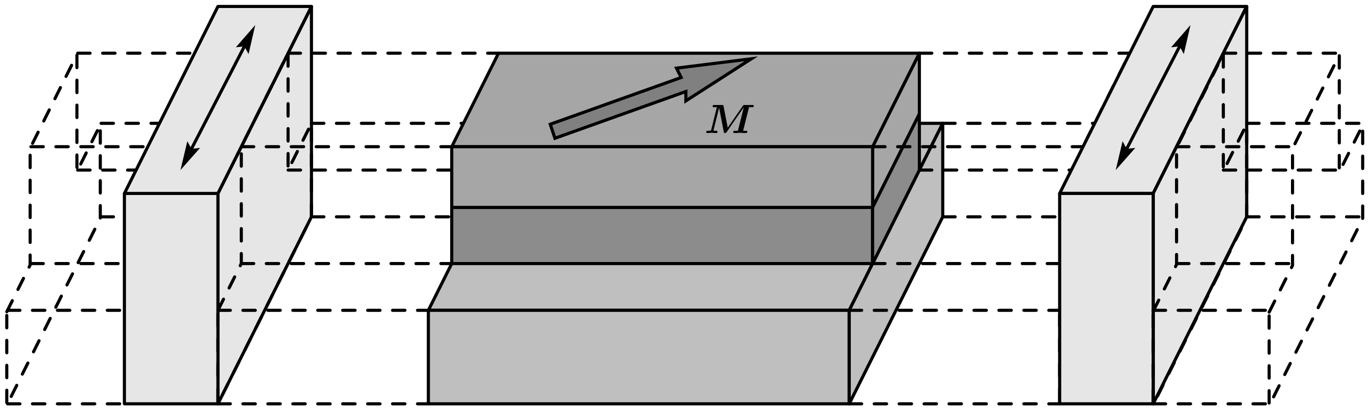
Conventional microoptic setup:



Polarizer, 0° | 45° nonreciprocal Faraday-rotator | Polarizer, 45°

Integrated optical concept*:



Polarizer, transparent for TE light

Unidirectional magnetooptic polarization converter
TE $\longrightarrow$ TE
TM $\longleftarrow$ TE

Polarizer, transparent for TE light

* An investigation of planar devices:
T. Mizumoto, Y. Naito, *Waveguide-type optical isolator with in plane magnetization structure*, Vol. 1274 of SPIE Proceedings, 220–228 (1990).

Unidirectional magnetooptic polarization converters

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- Isolator concepts
- Magnetooptic waveguides
  - Permittivity
  - Coupled mode theory
  - Unidirectional polarization conversion
- Polarization splitters
- Circulator device

International Workshop on Optical Waveguide Theory and Numerical Modelling
Saint-Etienne, France *23 – 26 September 1999*

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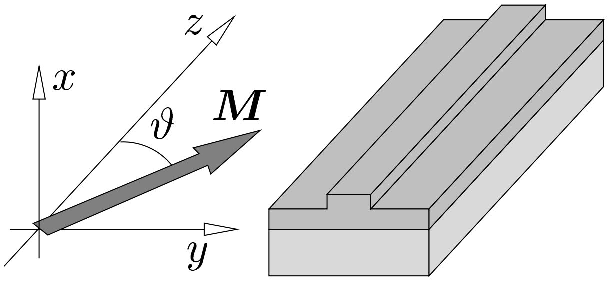
Permittivity of a waveguide made of magnetooptic garnet films:

n^2 — Guiding isotropic refractive index profile,

$+\,\delta\hat{\epsilon}_{\text{mo}}$ — Contribution due to the first order magnetooptic effect.

The magnetization

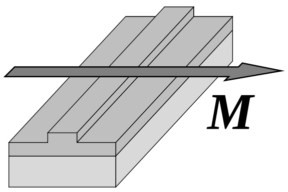
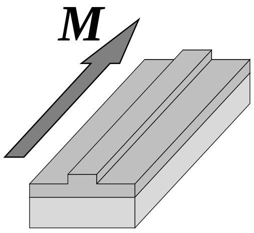
$$\boldsymbol{M} = M(0, \sin\vartheta, \cos\vartheta)$$



leads to the permittivity perturbation

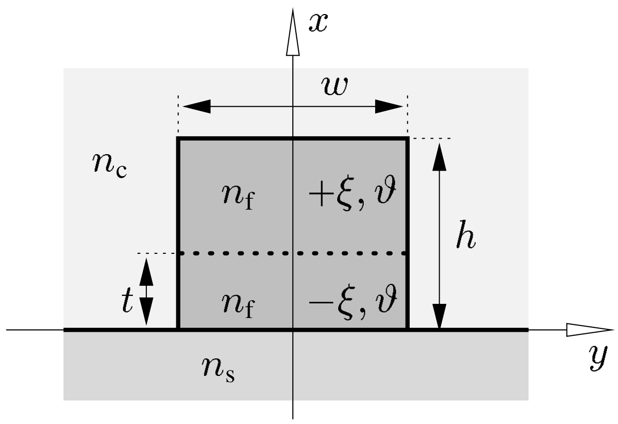
$$\delta\hat{\epsilon}_{\text{mo}} = \sin\vartheta\ \delta\hat{\epsilon}^{y}_{\text{mo}} + \cos\vartheta\ \delta\hat{\epsilon}^{z}_{\text{mo}}\,,$$

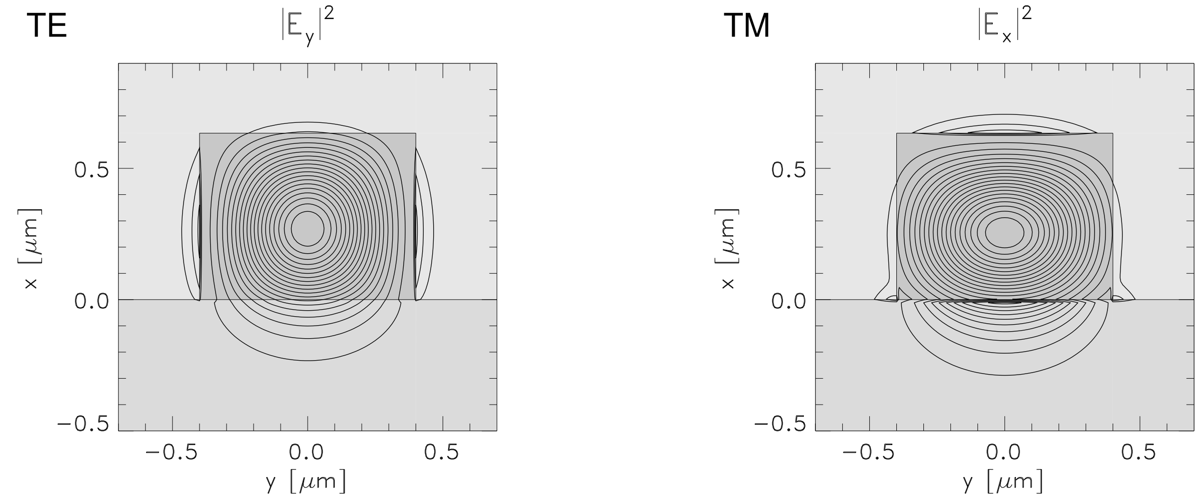
where

	
$\delta\hat{\epsilon}^{y}_{\text{mo}} = \begin{pmatrix} 0 & 0 & -\mathrm{i}\xi \\ 0 & 0 & 0 \\ \mathrm{i}\xi & 0 & 0 \end{pmatrix},$	$\delta\hat{\epsilon}^{z}_{\text{mo}} = \begin{pmatrix} 0 & \mathrm{i}\xi & 0 \\ -\mathrm{i}\xi & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}.$

$KM/\mathrm{i} = \xi = n\lambda\Theta_{\text{F}}/\pi$ with vacuum wavelength λ and specific Faraday-rotation Θ_{F}.

$$|\xi| \ll n^2 \quad\longrightarrow\quad \text{perturbation theory} \ldots$$





$$\begin{pmatrix} \boldsymbol{\mathcal{E}} \\ \boldsymbol{\mathcal{H}} \end{pmatrix}(x,y,z,t) = \sum_m C_m(z) \frac{1}{\sqrt{P_m}} \begin{pmatrix} \boldsymbol{E_m} \\ \boldsymbol{H_m} \end{pmatrix}(x,y)\, \mathrm{e}^{\mathrm{i}\omega t}, \quad m = \mathrm{TE}, \mathrm{TM}\,,$$

$$\boldsymbol{C} = \begin{pmatrix} C_\mathrm{TE} \\ C_\mathrm{TM} \end{pmatrix}.$$

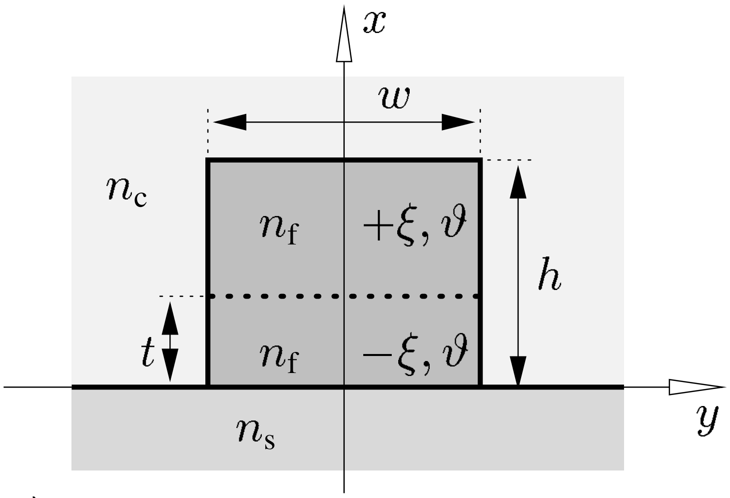
- Light propagation in the isotropic waveguide: $(\delta\hat{\epsilon}_\mathrm{mo} = 0)$:

$$\mathrm{i}\partial_z \boldsymbol{C} = \begin{pmatrix} \beta_\mathrm{TE} & 0 \\ 0 & \beta_\mathrm{TM} \end{pmatrix} \boldsymbol{C} \quad \rightarrow \quad \boldsymbol{C}(z) = \begin{pmatrix} \mathrm{e}^{-\mathrm{i}\beta_\mathrm{TE} z} & 0 \\ 0 & \mathrm{e}^{-\mathrm{i}\beta_\mathrm{TM} z} \end{pmatrix} \boldsymbol{C}(0)\,.$$

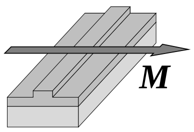
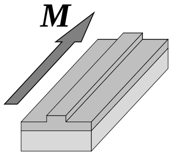
- Magnetooptic effects included:

$$\mathrm{i}\partial_z \boldsymbol{C} = \begin{pmatrix} \beta_\mathrm{TE} & 0 \\ 0 & \beta_\mathrm{TM} \end{pmatrix} \boldsymbol{C} + \begin{pmatrix} \kappa_\mathrm{TE,TE} & \kappa_\mathrm{TE,TM} \\ \kappa^*_\mathrm{TE,TM} & \kappa_\mathrm{TM,TM} \end{pmatrix} \boldsymbol{C}\,,$$

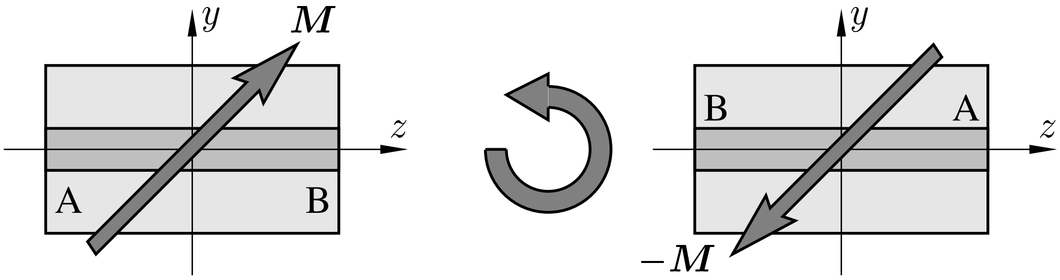
$$\kappa_{l,m} = \frac{\omega\epsilon_0}{4\sqrt{P_l P_m}} \iint \boldsymbol{E}_l^* \delta\hat{\epsilon}_\mathrm{mo} \boldsymbol{E}_m \, \mathrm{d}x\, \mathrm{d}y\,.$$

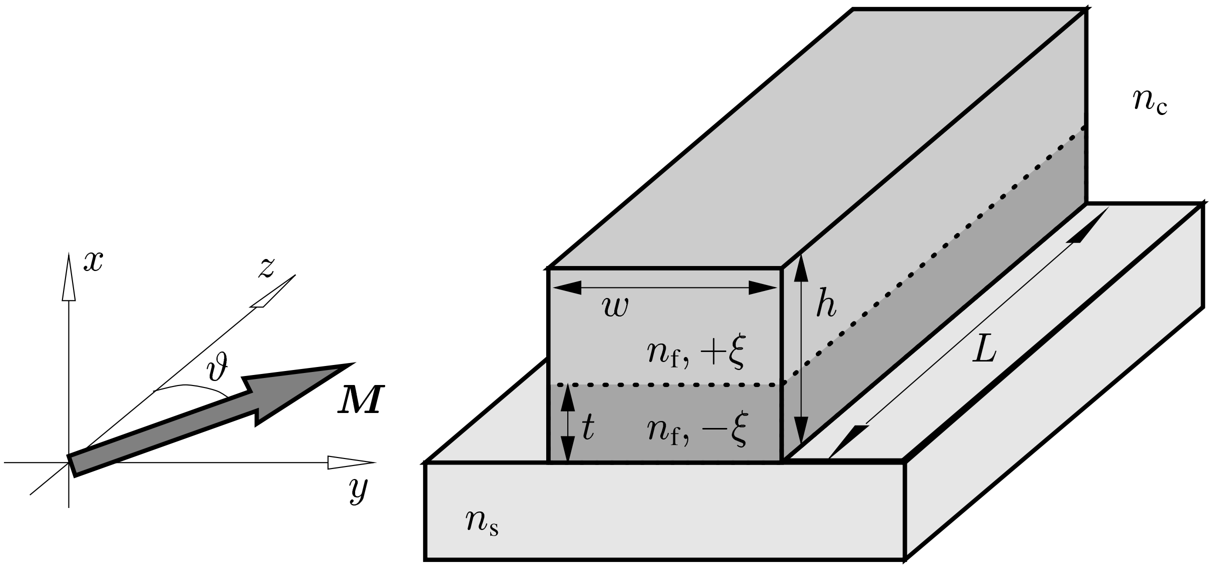


$$\begin{pmatrix} n \\ \delta\hat{\epsilon}^j_{\mathrm{mo}} \end{pmatrix}(y) = \begin{pmatrix} n \\ \delta\hat{\epsilon}^j_{\mathrm{mo}} \end{pmatrix}(-y) \qquad\qquad \gamma = \frac{\omega\epsilon_0}{4\sqrt{P_l P_m}}\,.$$

	TE-PS $\Delta\beta_{\mathrm{TE}}/2 = \kappa_{\mathrm{TE,TE}}$	TM-PS $\Delta\beta_{\mathrm{TM}}/2 = \kappa_{\mathrm{TM,TM}}$	TE/TM-CV $\kappa = \kappa_{\mathrm{TE,TM}}$
 $\delta\hat{\epsilon}^y_{\mathrm{mo}}$	≈ 0	$2\gamma \iint \xi E^{\mathrm{TM}}_x E^{\mathrm{TM}}_z \,\mathrm{d}x\,\mathrm{d}y$	0
 $\delta\hat{\epsilon}^z_{\mathrm{mo}}$	0	0	$\approx -\mathrm{i}\gamma \iint \xi E^{\mathrm{TE}}_y E^{\mathrm{TM}}_x \,\mathrm{d}x\,\mathrm{d}y$

Propagation in forward/backward direction $\leftrightarrow$ signs of ξ:





Degree of polarization conversion:

$$\eta(z) = \left|\frac{C_{TM}(z)}{C_{TE}(0)}\right|^2 = \frac{|\kappa|^2}{(\Delta\beta/2)^2 + |\kappa|^2}\,\sin^2\left(\frac{\pi}{2}\,\frac{z}{L_c}\right)\ ,$$

$C_{TM}(0) = 0, \qquad \Delta\beta = \beta_{TE} - (\beta_{TM} \pm \delta\beta_{TM})\ .$

Conversion length:

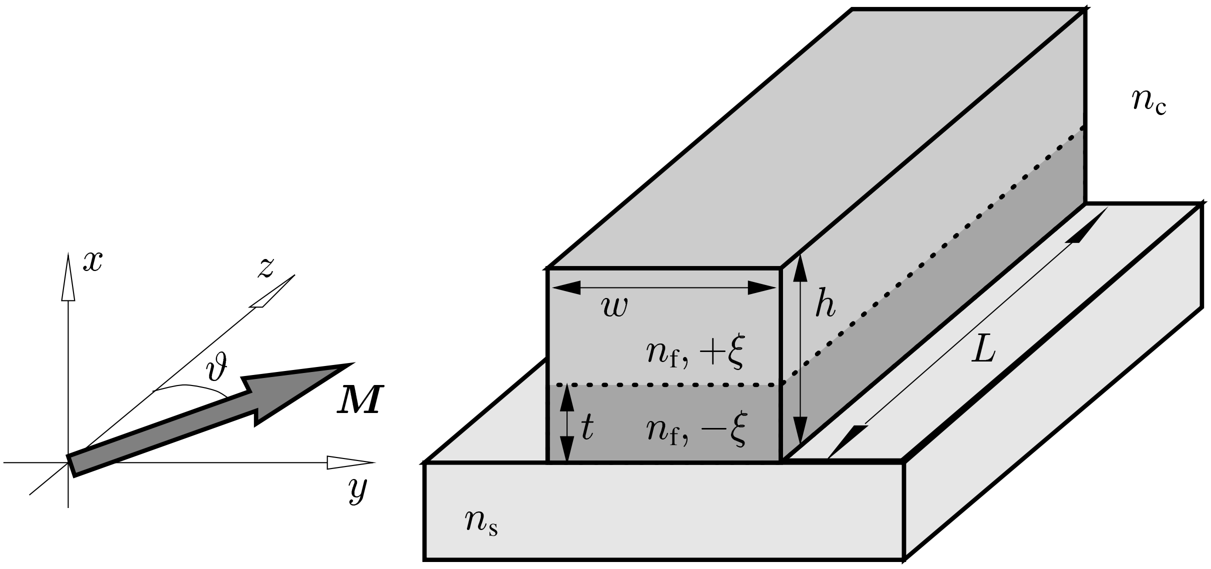
$$L_c = \frac{\pi}{2\sqrt{(\Delta\beta/2)^2 + |\kappa|^2}}\ .$$

Constraint for complete conversion:

Phase matching $\Delta\beta = 0$.

$\Rightarrow$ $\Leftarrow$

$$\left.\begin{array}{c} \Delta\beta^f = \beta_{TE} - \beta_{TM} - \delta\beta_{TM} \\ L_c^f \\ \eta_{max}^f \end{array}\right\} \neq \left\{\begin{array}{c} \Delta\beta^b = \beta_{TE} - \beta_{TM} + \delta\beta_{TM} \\ L_c^b \\ \eta_{max}^b \end{array}\right.$$



Choose parameters such that

$$\Delta\beta^\mathrm{b} = 0, \quad \text{i.e.} \;\; \eta^\mathrm{b}_\mathrm{max} = 1,$$

and

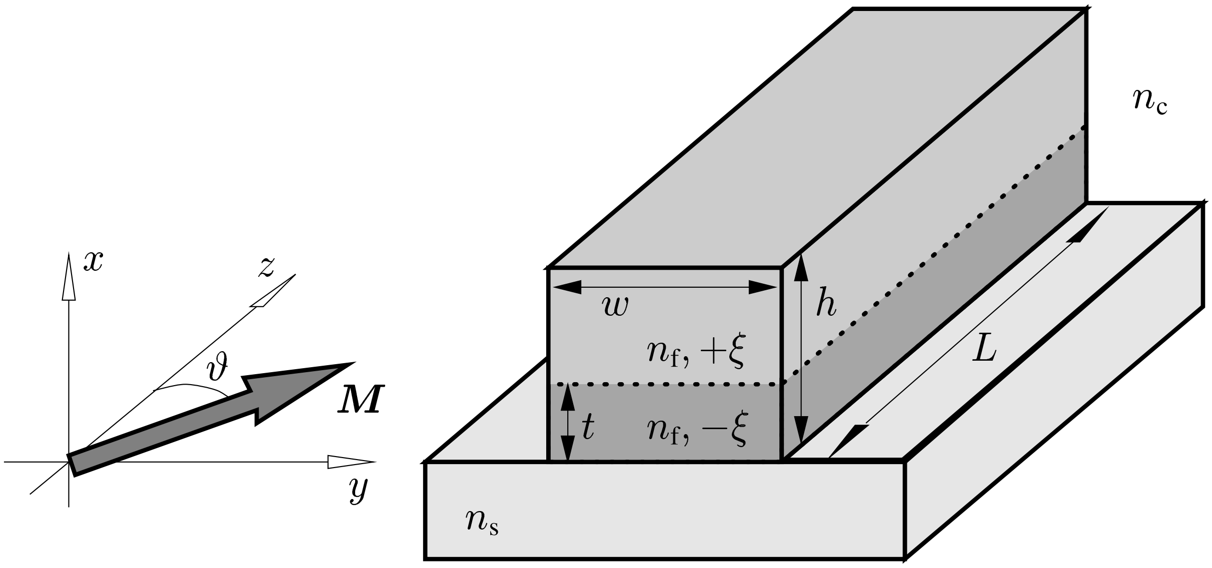
$$L = L^\mathrm{b}_\mathrm{c} = 2L^\mathrm{f}_\mathrm{c}.$$

$\longrightarrow$ No polarization conversion in forward direction,
but complete conversion for backwards propagating light !

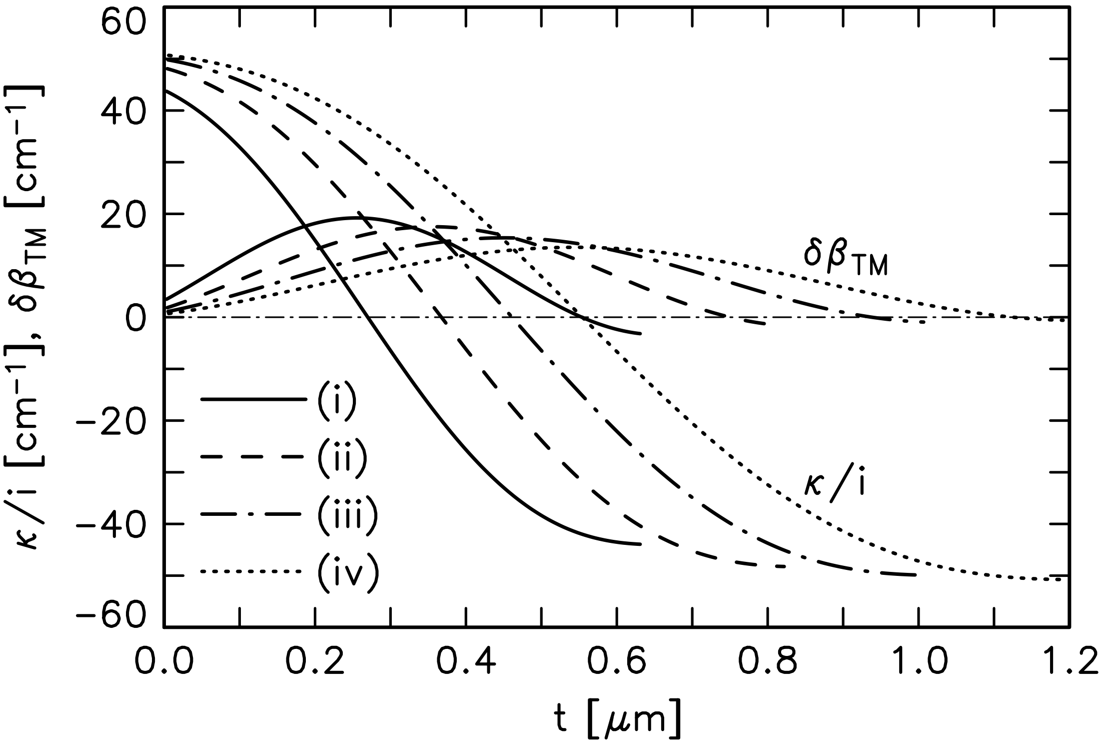
Conditions for ideal unidirectional polarization conversion:

$$|\delta\beta_\mathrm{TM}| = \sqrt{3}|\kappa| \qquad \text{and} \qquad \Delta\beta^\mathrm{b} = 0\,.$$

Device length: $\quad L = \dfrac{\pi}{2|\kappa|}\,.$

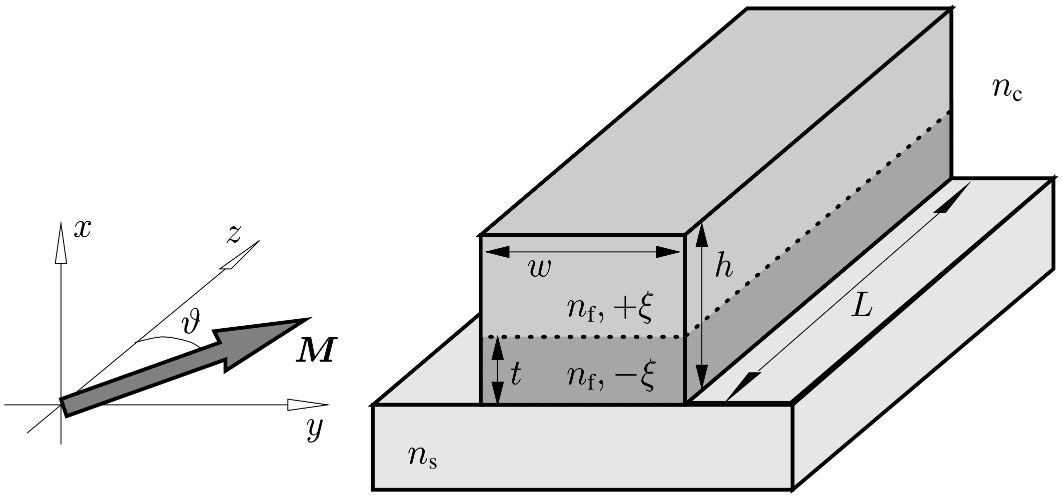


Maximum nonreciprocal TM phase shift $\delta\beta_{TM} = \kappa_{TM,TM}$ $(\vartheta = \pi/2)$
and maximum polarization conversion $\kappa = \kappa_{TE,TM}$ $(\vartheta = 0)$:



	(i)	(ii)	(iii)	(iv)
$h/\,\mu$m	0.634	0.826	1.012	1.198
$w/\,\mu$m	0.798	0.995	1.191	1.387

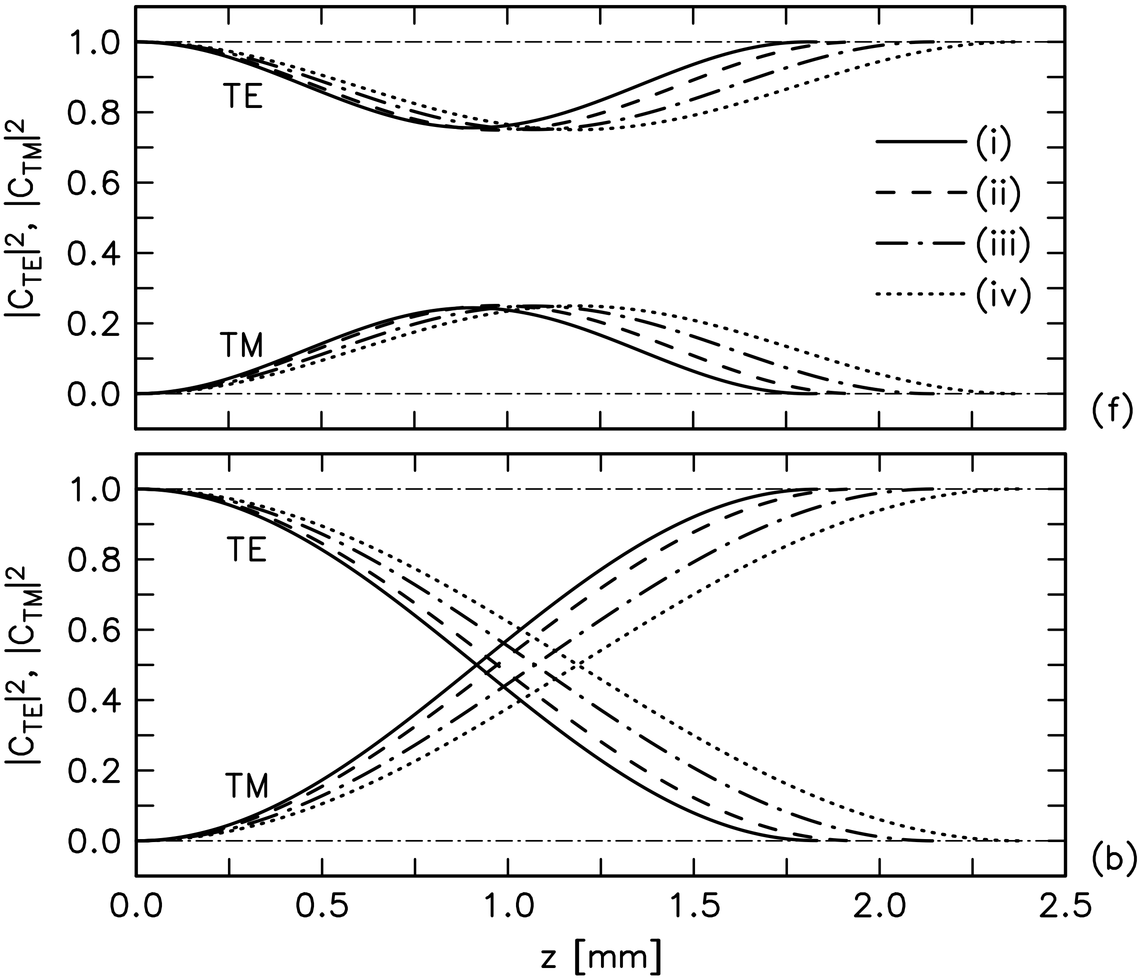
$n_s = 1.95$, $n_f = 2.302$, $n_c = 1.0$,
$\xi = 0.005$, $\lambda = 1.3\,\mu$m.

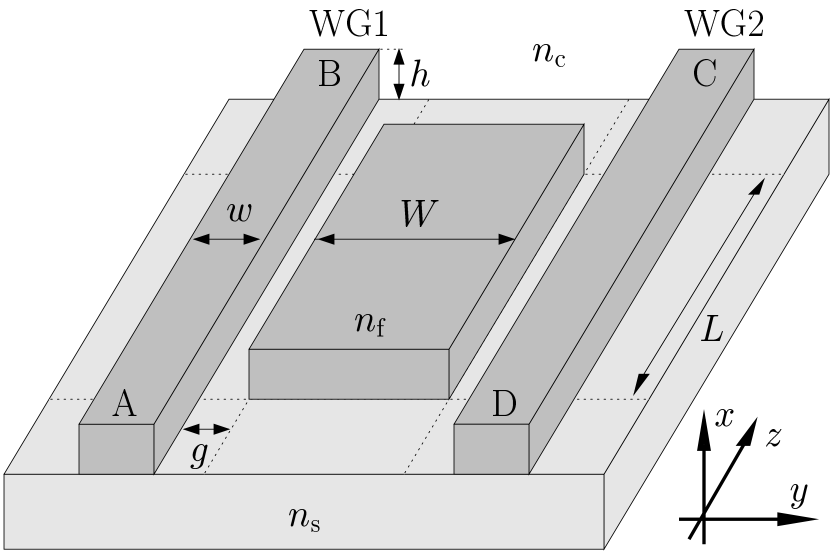


Geometries for unidirectional polarization converters:

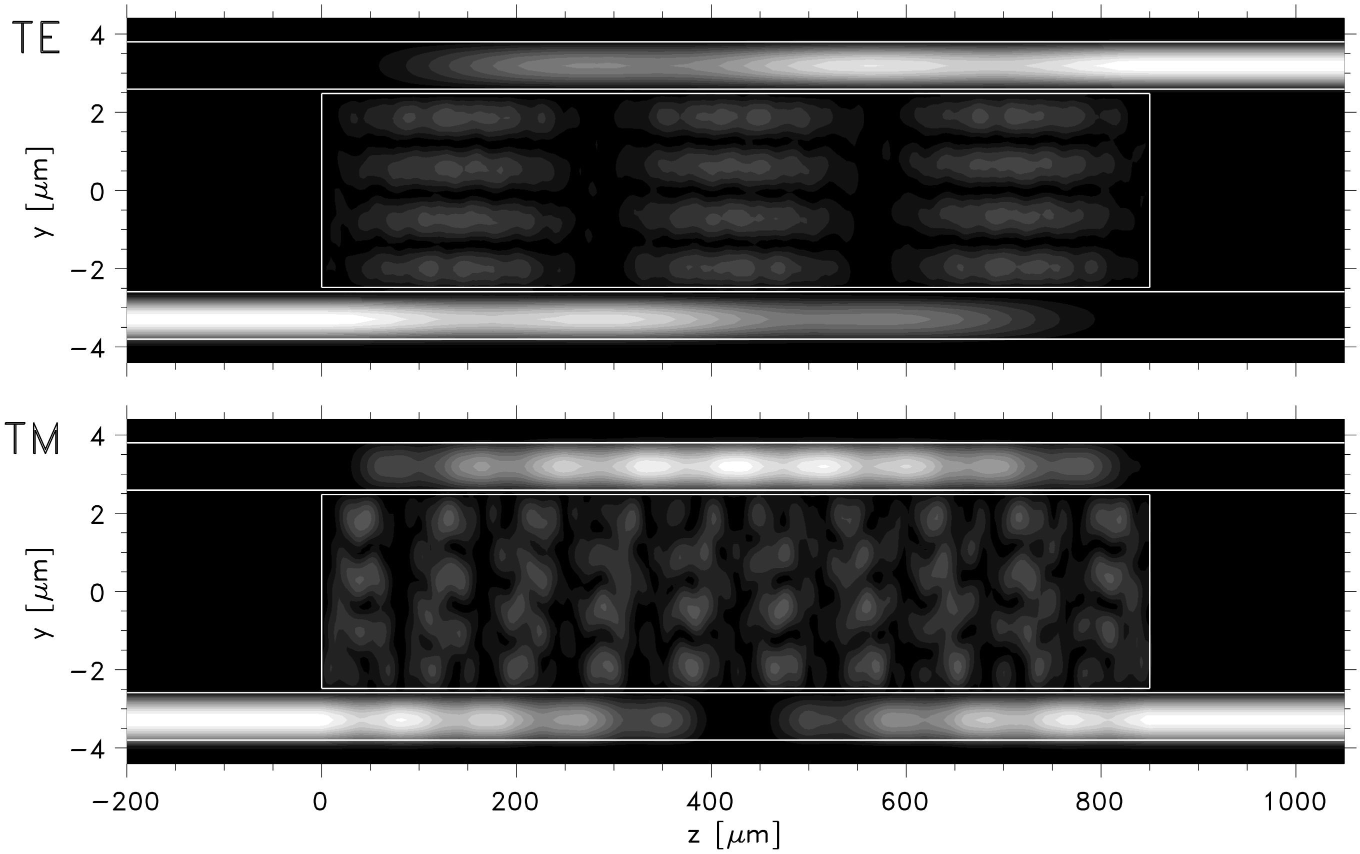
	$h/\,\mu$m	$w/\,\mu$m	$t/\,\mu$m	$\vartheta/^\circ$	$L/$ mm
(i)	0.634	0.789	0.181	63	1.83
(ii)	0.826	0.995	0.264	65	1.94
(iii)	1.012	1.191	0.349	66	2.14
(iv)	1.198	1.387	0.431	68	2.38

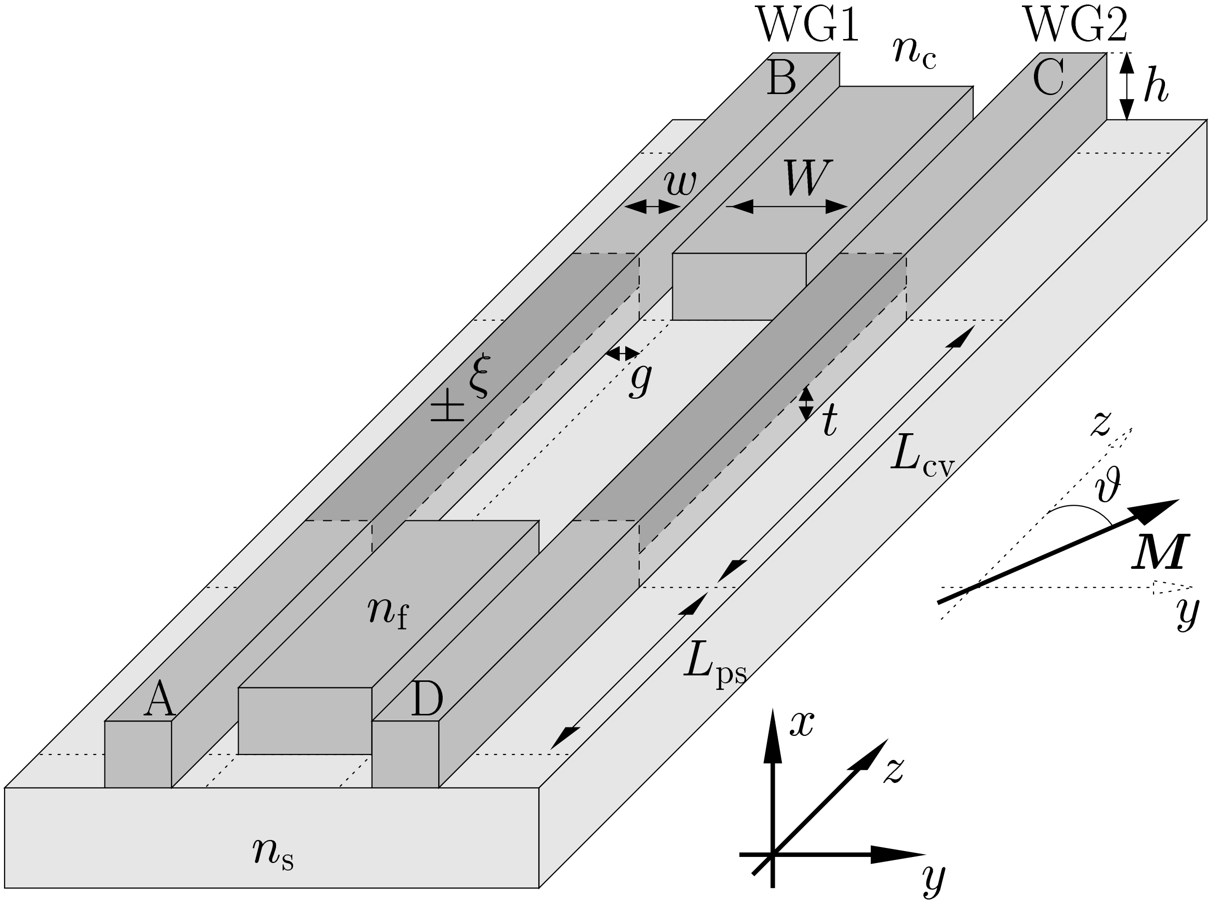
$n_s = 1.95$,
$n_f = 2.302$,
$n_c = 1.0$,
$\xi = 0.005$,
$\lambda = 1.3\,\mu$m.



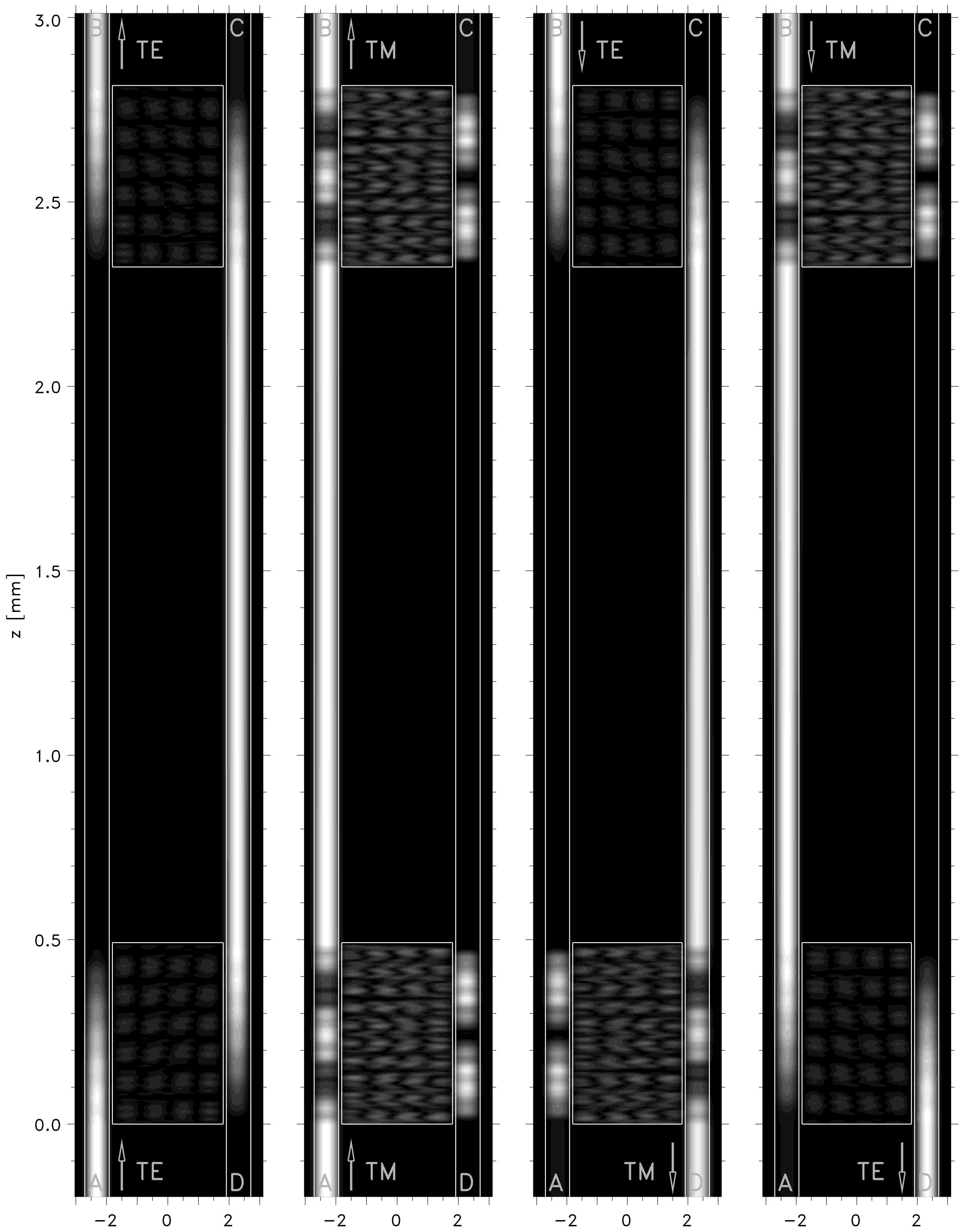


W	w	g	h	λ	L	n_s	n_f	n_c
4.96 μm	1.21 μm	0.11 μm	0.70 μm	1.30 μm	850 μm	1.95	2.2	1.0

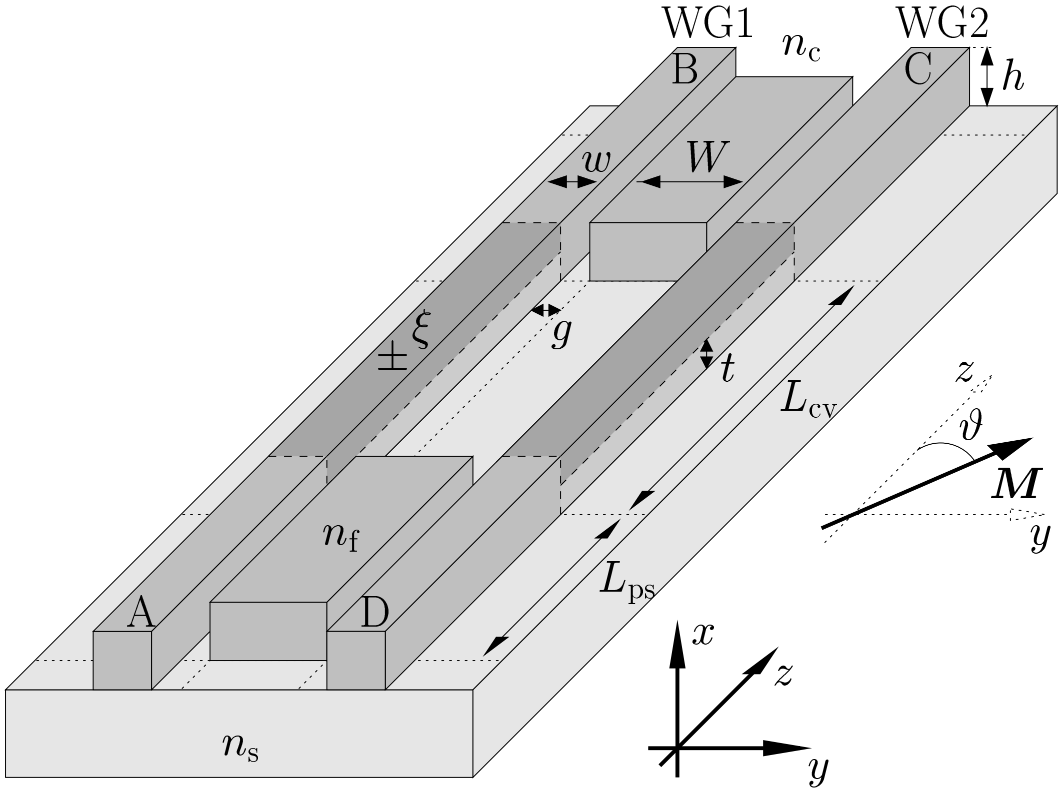




h/μm	w/μm	t/μm	$\vartheta/\,^\circ$	g/μm	W/μm	L_{ps}/μm	L_{cv}/μm	n_s	n_f	n_c	$\pm\xi$	λ/μm
0.634	0.798	0.181	63	0.103	3.616	492	1832	1.95	2.302	1.0	0.005	1.3



(a) **(b)** **(c)** **(d)**



- Magnetooptic waveguides with tilted in-plane magnetization: Combination of nonreciprocal phase shift and polarization conversion
- Coupled mode theory for hybrid fundamental modes of raised strip waveguides
- Unidirectional polarization conversion
- Radiatively coupled waveguide polarization splitters
- Concept for a polarization independent integrated circulator device