news & views: A Chip-scale One-way Valve For Light

S. J. Ben Yoo
Department of Electrical and Computer Engineering, University of California, Davis, California 95916, USA

Complete Optical Isolation Created by Indirect Interband Photonic Transitions

Zongfu Yu[1] and Shanhui Fan[2]
[1] Department of Applied Physics, Stanford University, Stanford, California 94305, USA
[2] Department of Electrical Engineering, Stanford University, Stanford, California 94305, USA

Wolfgang Freude

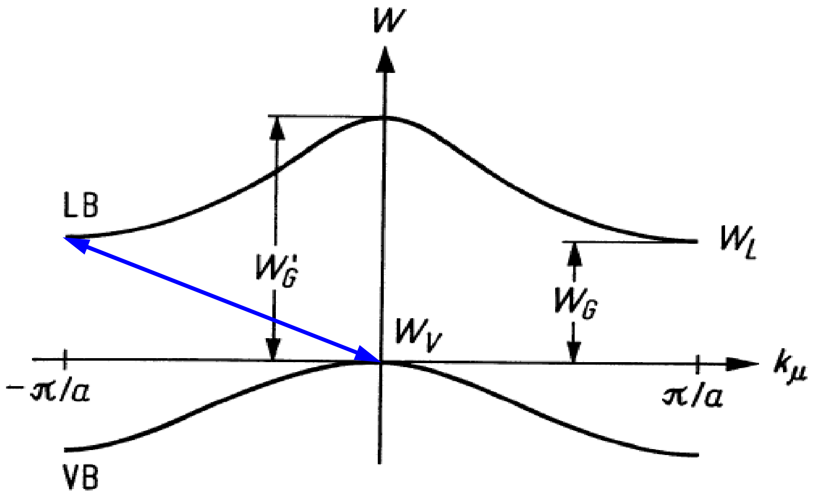
Institute of Photonics and Quantum Electronics (IPQ), University of Karlsruhe, Germany

Universität Karlsruhe (TH)
Institut für Photonik und Quantenelektronik (IPQ)
http://www.ipq.uni-karlsruhe.de

NATURE PHOTONICS | VOL 3 | FEBRUARY 2009 | www.nature.com/naturephotonics

Sem IPQ Wed, Feb 04, 2009

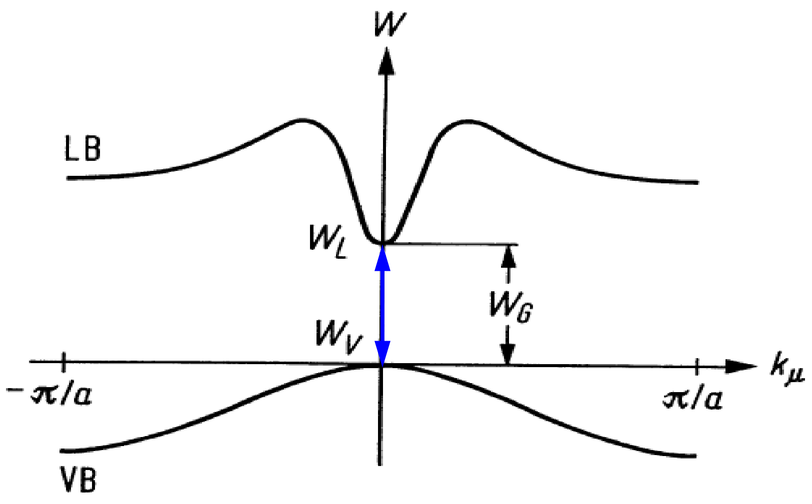
Direct and Indirect Semiconductors



Indirect semicond. Smallest transition energy W_G for crystal momentum difference $\Delta k_\mu = \pi/a$. Phonon required for collision. Examples: Elemental semiconductors Si, Ge

$$W_G = \begin{cases} 0{,}67\,\text{eV} \mathrel{\widehat{=}} 1{,}85\,\mu\text{m} & \text{(Ge)} \\ 1{,}13\,\text{eV} \mathrel{\widehat{=}} 1{,}10\,\mu\text{m} & \text{(Si)} \end{cases}$$

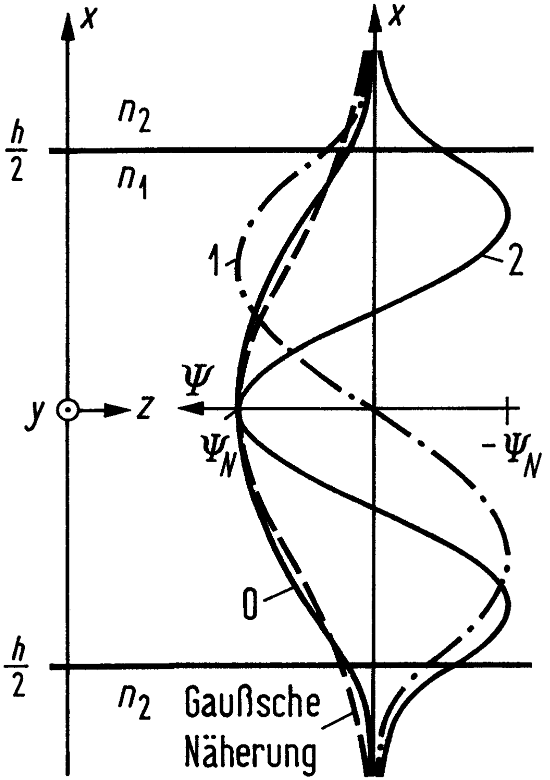
$$W_G' = \begin{cases} 0{,}8\ \ \text{eV} \mathrel{\widehat{=}} 1{,}55\,\mu\text{m} & \text{(Ge)} \\ 3{,}4\ \ \text{eV} \mathrel{\widehat{=}} 0{,}36\,\mu\text{m} & \text{(Si)} \end{cases}$$



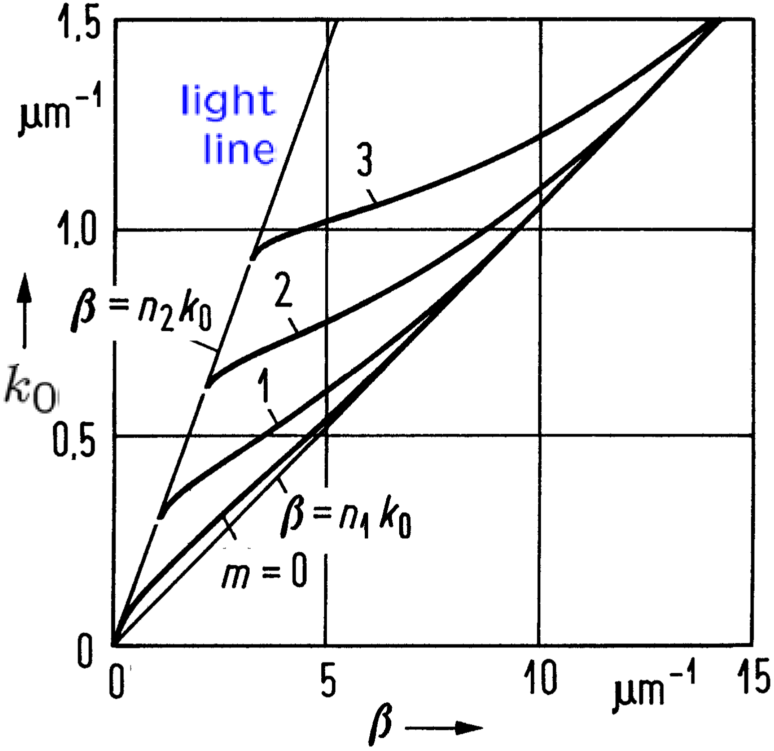
Direct semicond. Smallest transition energy W_G for crystal momentum difference $\Delta k_\mu = 0$. No collision partner required. Examples: Compounds GaAs, InP, InGaAs

$$W_G = \begin{cases} 1{,}42\,\text{eV} \mathrel{\widehat{=}} 0{,}87\,\mu\text{m} & \text{(GaAs)} \\ 1{,}80\,\text{eV} \mathrel{\widehat{=}} 0{,}69\,\mu\text{m} & (\text{Ga}_{0{,}7}\text{Al}_{0{,}3}\text{As}) \\ 0{,}75\,\text{eV} \mathrel{\widehat{=}} 1{,}65\,\mu\text{m} & (\text{In}_{0{,}53}\text{Ga}_{0{,}47}\text{As}) \\ 1{,}35\,\text{eV} \mathrel{\widehat{=}} 0{,}92\,\mu\text{m} & \text{(InP)} \end{cases}$$

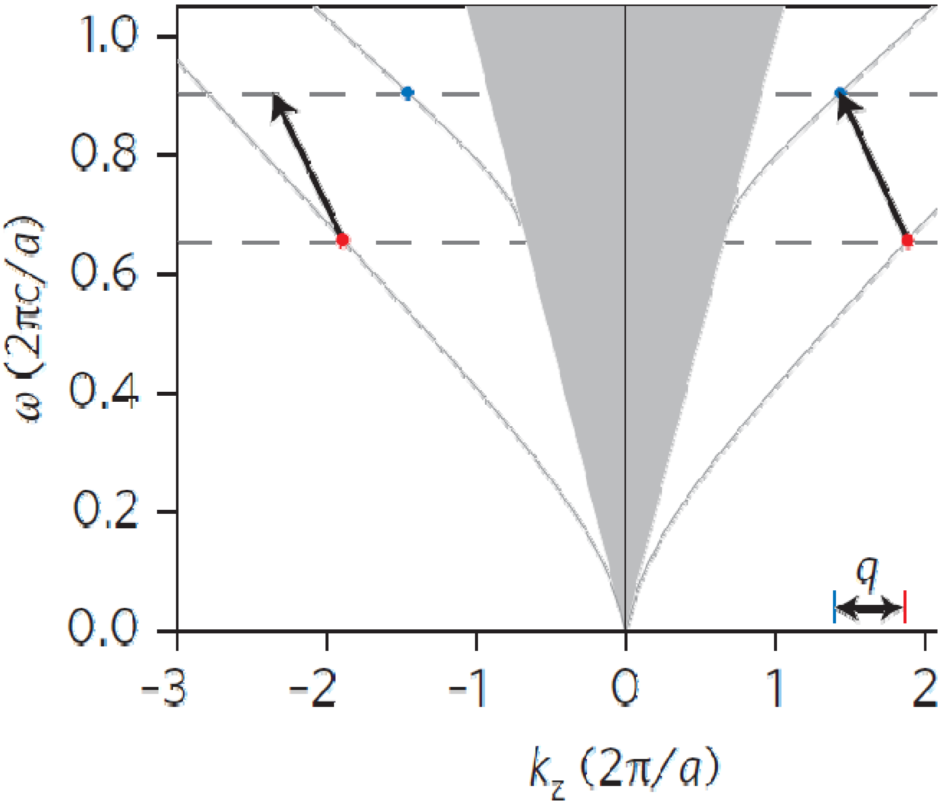
Slab Waveguide and Dispersion Diagram

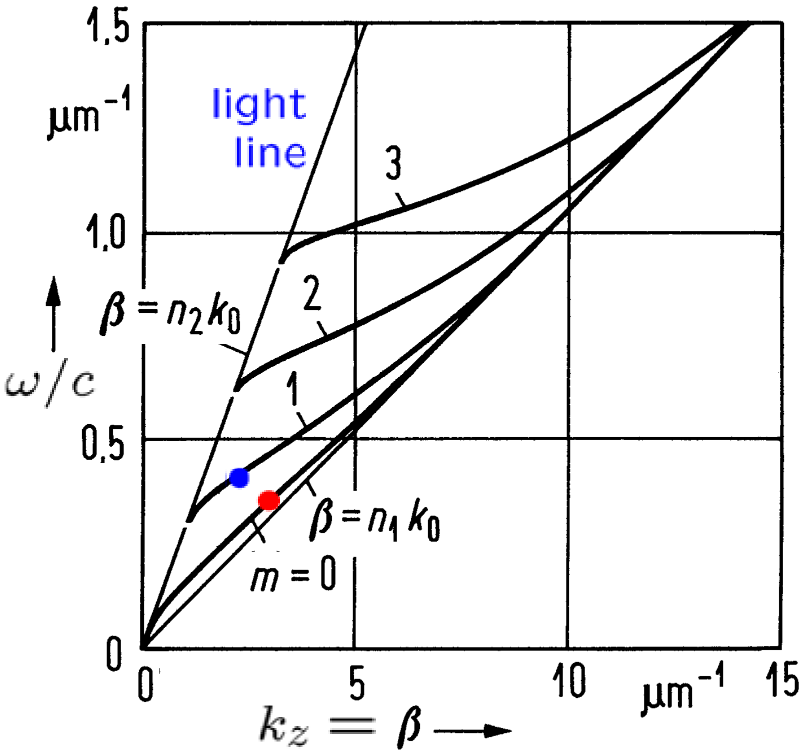


$$\frac{\omega}{c} = \frac{2\pi}{\lambda} = k_0$$



Dispersion Diagram and Indirect 0-Band to 1-Band Transitions





Transition chosen for matching group velocities.

Brillouin Scattering

Brillouin scattering: Pump carrier f_p modulated by thermal molecular vibrations with frequency f_μ. Resulting light frequency-shifted down by $\Delta f_B = f_p - f_B$ ($\approx 15\,\text{GHz}$ for $\lambda_p = 1\,\mu\text{m}$, $\Delta f_{pH} < 38\,\text{MHz}$) from pump frequency to $f_B = f_p - f_\mu$.

Momentum conservation: $\vec{k}_p = \vec{k}_B + \vec{k}_\mu$ is true, if pump f_p and phonon “grating” f_μ propagate forward, while frequency down-shifted light f_B propagates backwards.

Frequency down-shifted light travels opposite to “grating” which runs away from pump light (Doppler effect, $f_\mu = 2nv_{\text{acoustic}}/\lambda_p$).

Fundamental to Higher-Order Mode Coupling & Frequency Shift

Pump frequency travelling to the right ⇒
Refractive index grating travelling to the left ⇐
Frequency up-shifted light travelling to the right ⇒

Pump frequency travelling to the left ⇐
Refractive index grating travelling to the left ⇐
Frequency up-shifted light does not exist: No phase matching!

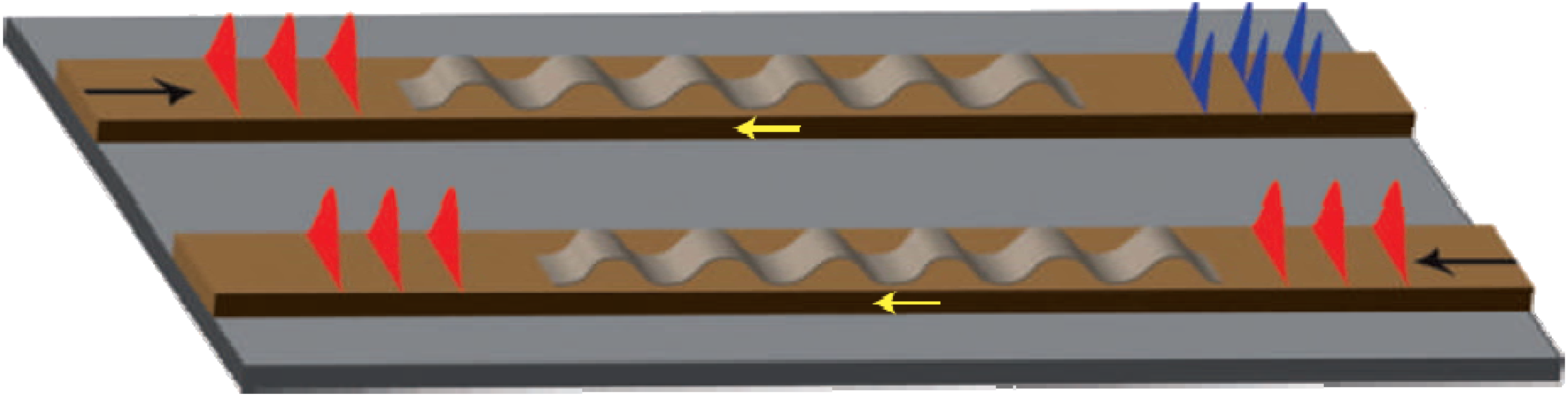


Illustration of how a travelling (dynamic) modulation of a silicon waveguide's refractive index can be used to perform optical isolation. The modulation induces a wavevector shift on light pulses (red) travelling from left to right, whereas pulses travelling right to left experience no such change. An optical filter can be used to separate the shifted and non-shifted pulses.

Mode Coupling & Frequency Shift with OBPF → Isolation

Required modulation profile at RF frequency (e. g., $f_{\text{mod}} = 20\,\text{GHz}$), but propagation constant corresponding to light wavelength (e. g., $k_z = 2\pi \times 1\,\mu\text{m}^{-1}$).

Achieved by standing-wave modulation of a set of discrete regions, each modulated at a different phase.

Matching v_g: $\delta n_{\text{mod}} = 5 \times 10^{-4}$, WG width 270 nm, BW = 1.2 THz

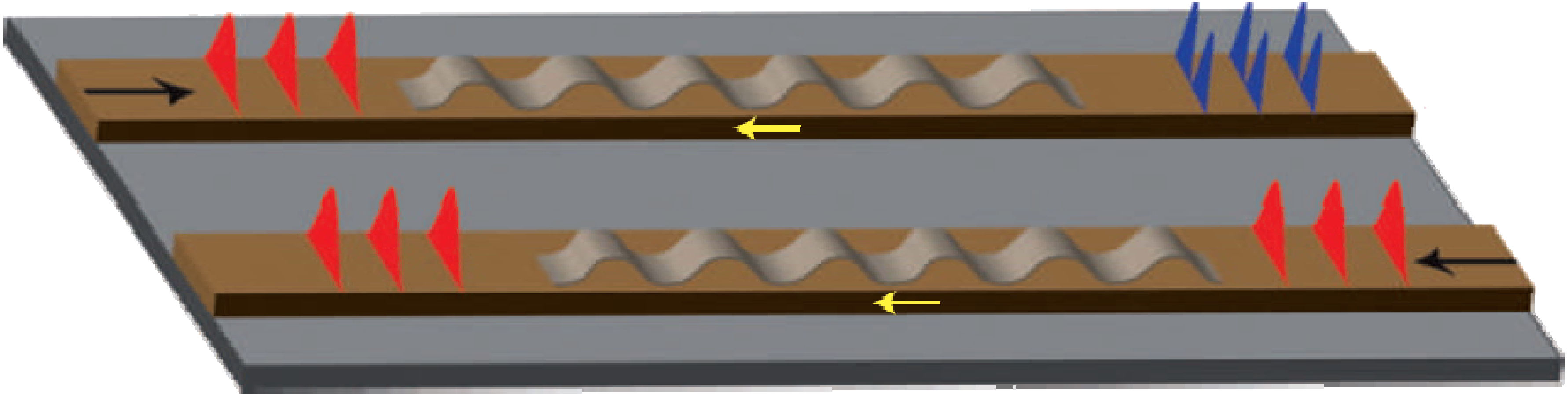
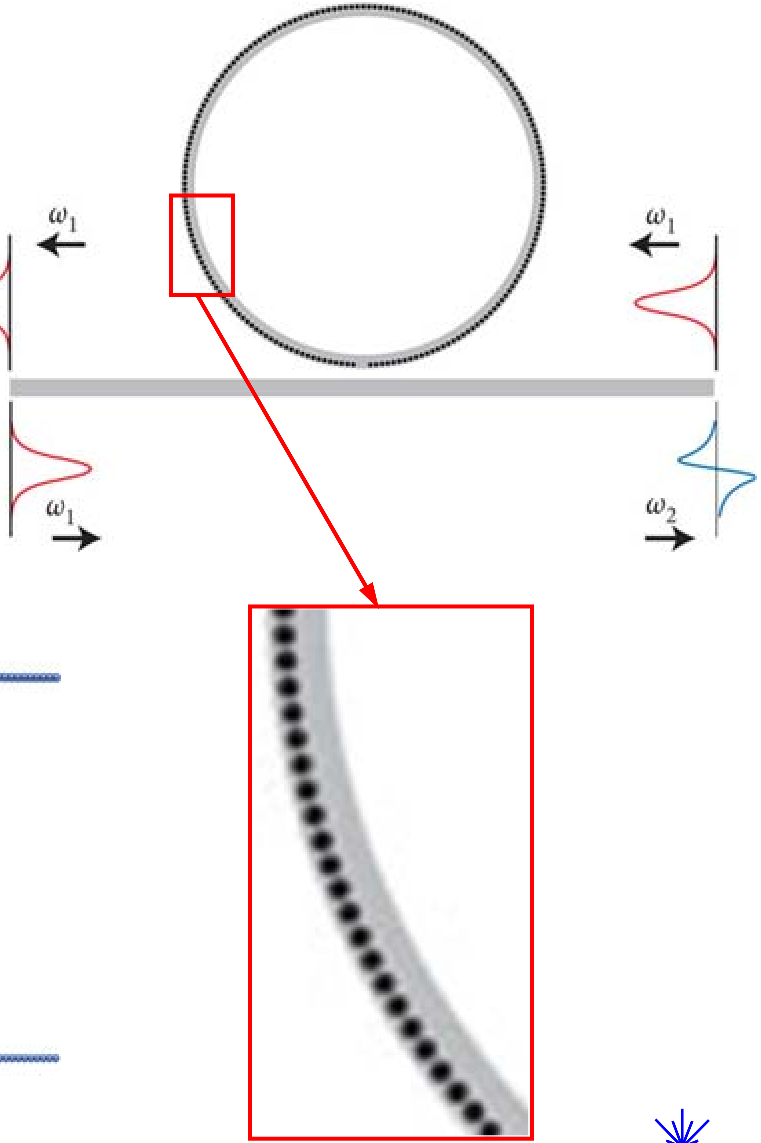
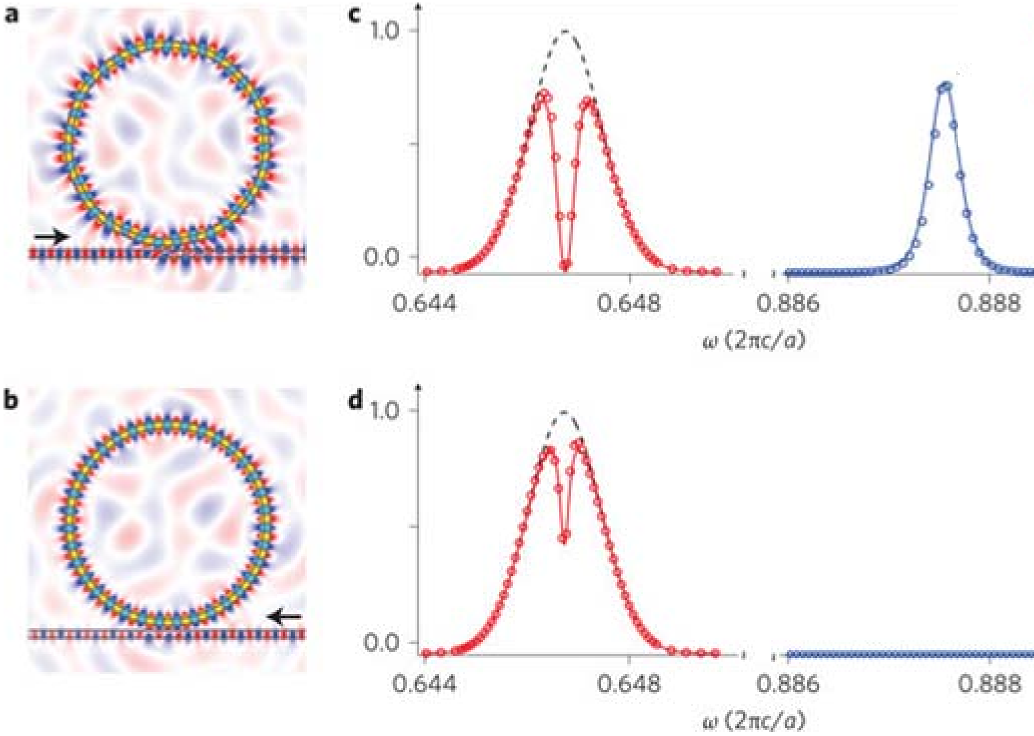


Illustration of how a travelling (dynamic) modulation of a silicon waveguide's refractive index can be used to perform optical isolation. The modulation induces a wavevector shift on light pulses (red) travelling from left to right, whereas pulses travelling right to left experience no such change. An optical filter can be used to separate the shifted and non-shifted pulses.

Ring Resonator for Nonreciprocal Frequency Conversion

Dark regions are modulated: rod diameter $= 0.08a$, rod spacing $= 0.1a$, centres on circle $R = 3.08a$





Same Principles Apply When Using Surface Acoustic Waves

Pump frequency travelling to the right ⇒

SAW refractive index grating travelling to the left ⇐

Freq. up-shifted orthog. pol. light travelling to the right ⇒

Pump frequency travelling to the left ⇐

SAW refractive index grating travelling to the left ⇐

Freq. up-shifted orthog. pol. light does not exist: No phase match!

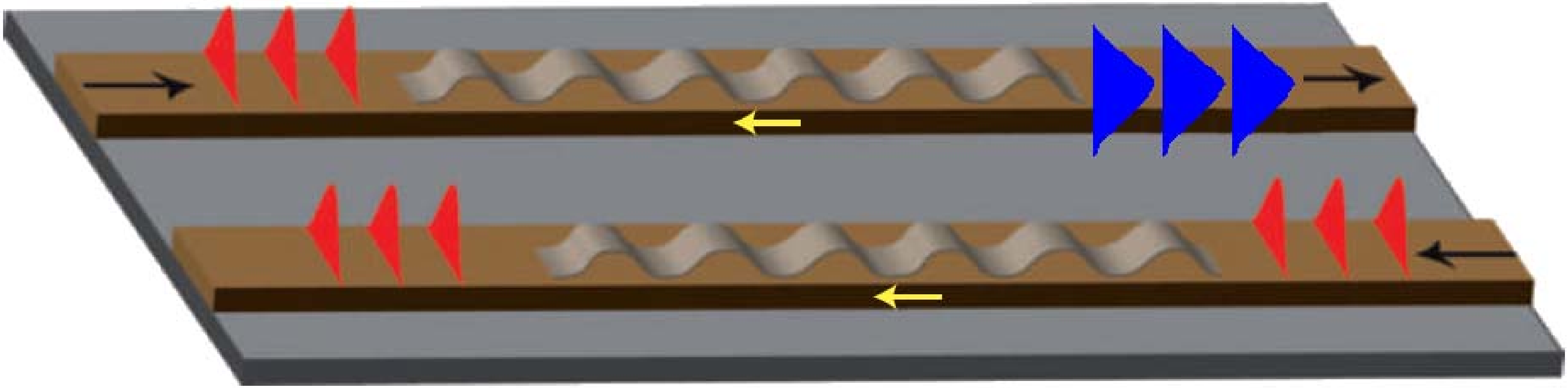


Illustration of how a travelling (dynamic) modulation of a silicon waveguide's refractive index can be used to perform optical isolation. The modulation induces a wavevector shift on light pulses (red) travelling from left to right, whereas pulses travelling right to left experience no such change. An optical **polarization** filter can be used to separate the shifted and non-shifted pulses.

Polarization Mode Coupling by Surface Acoustic Wave

SAW refractive index grating $\mathrm{LiNbO_3}$: $f_{\mathrm{mod}} \approx 170\,\mathrm{MHz}$, $\lambda_{\mathrm{mod}} \approx 20\,\mu\mathrm{m}$, $v \approx 3\,700\,\mathrm{m/s}$, $k_{\mathrm{mod}} = \frac{\omega_{\mathrm{mod}}}{v} \approx 0.3\,\mu\mathrm{m}^{-1}$

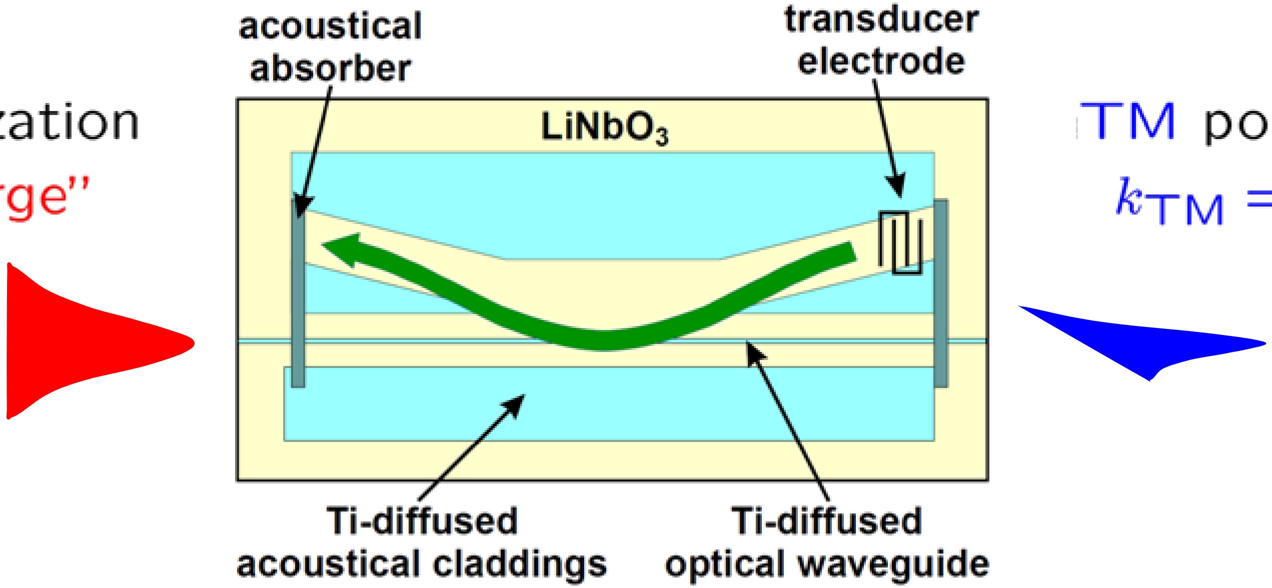
E. g., fibre PMD: $\Delta t_g = 0.1 \frac{\mathrm{ps}}{\sqrt{\mathrm{km}}} \rightarrow \Delta k_{\mathrm{TE-TM}} \overset{1.5\,\mu\mathrm{m}}{\approx} \omega \frac{\Delta t_g}{L} \approx 0.1\,\mu\mathrm{m}^{-1}$

TE polarization

$k_{\mathrm{TE}} =$ “large”

TM polarization

$k_{\mathrm{TM}} =$ “small”



J. Frangen, H. Herrmann, R. Ricken, H. Seibert, W. Sohler: Integrated optical, acoustically tunable wavelength filter. Electron. Lett., Vol. 25, pp. 1583-1585 (1989)

H. Herrmann, St. Schmid: Integrated acoustooptical mode converters with weighted coupling using surface acoustic wave directional couplers. Electron. Lett, Vol. 28, pp.979-981 (1992)

H. Herrmann, U. Rust, K. Schäfer: Tapered acoustical directional couplers for integrated acoustooptical mode converters with weighted coupling. J. Lightw. Technol., Vol.13, pp. 364-374 (1995)

H. Herrmann, H. Mendis: Broadly tunable integrated acoustooptical polarization converters in $\mathrm{LiNbO_3}$. Proc. 9th European Conference on Integrated Optics (ECIO'99), Torino, April 1999, pp. 229-232