Dielectric Waveguide Amplifiers and Lasers

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The goal of integrated optics

Integrate on a single micro-chip:

- Lasers
- Amplifiers
- Modulators
- Splitters
- Wavelength routers
- Spectrometers
- Interferometers
- Detectors
- Interaction with the environment
- Combination with electronics
The goal of integrated optics

Provide through on-chip optical integration:

- smaller size and weight
- inherently high spatial resolution
- reduction of coupling losses
- avoidance of mechanical instabilities
- avoidance of the necessity for alignment
- enormous cost reduction
- potential for mass fabrication

in order to open a new horizon of optical applications in e.g., communication, sensing, biomedicine, and space
The materials battle in integrated optics

Electronics: The world of the silicon chip

Photonics: Many different materials
- Passive structures (splitters, routers, filters, etc.):
  - Silicon
  - Silicon nitride
  - Silicon oxide and other oxide glasses
- Nonlinear optics:
  - \( \text{LiNbO}_3 \)
  - Chalcogenide glass
  - Silicon
- Light generation and amplification:
  - III-V semiconductors (GaAlAs, InP, GaN)
  - Impurity doped crystals and glasses

Likely, the future will witness hybrid integration of materials.
1. Rare-earth-ion-doped high-gain amplifiers in potassium double tungstates

2. Rare-earth-ion-doped a-Al$_2$O$_3$ narrow-linewidth lasers on a silicon chip

3. Dual-wavelength lasers, microwave generation, and intra-laser-cavity optical sensing on a silicon chip
1. Rare-earth-ion-doped high-gain amplifiers in potassium double tungstates

2. Rare-earth-ion-doped $a\text{-Al}_2\text{O}_3$ narrow-linewidth lasers on a silicon chip

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Semiconductor gain materials:

1. Excitation of electron-hole pairs in semiconductors is accompanied with large refractive-index changes.
2. The lifetime of an electron-hole pair in a III-V semiconductor is typically in the range of 1-100 ps.

Both effects lead to strong spatial and temporal gain patterning effects.

Rare-earth-ion-doped gain materials:

1. temporally and spatially stable gain
2. high-speed amplification into Tb/s regime
3. distributed-feedback lasers with narrower linewidths
4. less time jitter in ultrafast-pulse generation
5. lower heat generation on chip, if diode pump external.
Optical amplifiers

Rare-earth-ion (Er$^{3+}$) doped fiber amplifiers:
+ low noise
+ negligible non-linearities
+ high-speed ($\sim$Tb/s) amplification
+ high overall gain of 30-50 dB
- several meters length

Semiconductor optical amplifiers (SOAs):
- low speed ($\sim$10 Gb/s) in saturated amplifier regime
- refractive index changes by e-h pairs
- temporal and spatial gain patterning effects
+ electrical pumping
+ high gain per unit length

⇒ SOAs are best choice for on-chip amplification.
Device gain: The physics

\[ g_{\text{mod}} = \Gamma g_{\text{mat}} = 4.34 \Gamma \sigma_{\text{em}} N_{\text{inv}} \]

modal gain = mode overlap \times material gain (dB/cm)

mode overlap (cm²)
emission cross-section (cm⁻²)
inversion density (cm⁻³)

Device gain: How to optimize?

\[ g_{mod} = \Gamma g_{mat} = 4.34 \Gamma \sigma_{em} N_{inv} \]

What do we need for high device gain?

1. high mode overlap \( \Gamma \) (between signal and active region)
2. high emission cross-section \( \sigma_{em} \) (of active species)
3. high inversion density \( N_{inv} \) (of active species)

# Device gain: Examples (integrated devices)

\[
g_{\text{mod}} = \Gamma g_{\text{mat}} = 4.34 \Gamma \sigma_{em} N_{\text{inv}}
\]

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Family of monoclinic potassium double tungstates
KY(WO$_4$)$_2$, KGD(WO$_4$)$_2$, KLu(WO$_4$)$_2$:

*M. Pollnau et al., IEEE J. Sel. Top. Quantum Electron 13, 661 (2007)*

Rare-earth ions doped into these crystals exhibit large absorption and emission cross-sections.

Task: improve also the mode confinement and inversion density!

⇒ competitive rare-earth-doped integrated amplifier?
Layer growth:
Liquid phase epitaxy of $\text{KY}_{1-x-y-z}\text{Gd}_x\text{Lu}_y\text{RE}_z(\text{WO}_4)_2$ layers on undoped $\text{KY(WO}_4)_2$ substrates in a $\text{K}_2\text{W}_2\text{O}_7$ solvent at $\sim 920^\circ\text{C}$ \(\Rightarrow\) 2-10 µm thick films (after polishing)

*D. Geskus et al., Opt. Express 18, 26107 (2010)*

Microstructuring:
Ar$^+$ beam etching through standard photoresist mask

*D. Geskus et al., Opt. Express 18, 8853 (2010)*

Overgrowth of $\text{KY(WO}_4)_2$ top cladding endface polishing

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**Waveguide fabrication**

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Co-doping of active layer

In $\text{KY}_{1-z}\text{RE}_z(\text{WO}_4)_2$ layers on $\text{KY(WO}_4)_2$ substrates, partial replacement of $Y^{3+}$ ions by $\text{Gd}^{3+}$ and $\text{Lu}^{3+}$ ions, resulting in $\text{KY}_{1-x-y-z}\text{Gd}_x\text{Lu}_y\text{RE}_z(\text{WO}_4)_2$ layers, simultaneously serves three purposes:

1) increased refractive index contrast between layer and substrate \(\Rightarrow\) better mode confinement,
2) increased doping concentration of active $\text{RE}^{3+}$ ion \(\Rightarrow\) better pump absorption and higher gain,
3) at simultaneous lattice matching \(\Rightarrow\) crack-free layers


Lattice matching by co-doping

KYW: Gd$^{3+}$, Lu$^{3+}$, Yb$^{3+}$

Matched \(\rightarrow\) Crack free!

Yb$^{3+}$ replaces Lu$^{3+}$ for lasing

Lattice-matched rare-earth-ion-doped layers

KY_{1-x-y-z}Gd_xLu_yRE_z(WO_4)_2 on undoped KY(WO_4)_2

Gd^{3+} increases, while Lu^{3+} decreases lattice

Choose correct fractions ⇒ lattice matching

Lu^{3+} / Yb^{3+} / Er^{3+} / Tm^{3+} have similar ion radii

⇒ large range of RE^{3+} concentrations up to ~ KGd_{0.5}RE_{0.5}(WO_4)_2


Refractive-index contrast

The refractive index quantifies the retardation of light travelling through matter as a result of interaction with the electron clouds of the atoms inside the matter.

The larger the electron density of an atom and the higher their density inside the matter, the higher is the refractive index.

\( \text{Gd}^{3+} \text{ vs. } \text{Y}^{3+} : \) Gd fills the inner 4f shell \( \Rightarrow \) higher e\(^{-}\) density
Gd widens the lattice \( \Rightarrow \) lower e\(^{-}\) density

\( \text{Lu}^{3+} \text{ vs. } \text{Y}^{3+} : \) Lu fills the inner 4f shell \( \Rightarrow \) higher e\(^{-}\) density
Lu narrows the lattice \( \Rightarrow \) higher e\(^{-}\) density

\( \Rightarrow \) mainly Lu increases the refractive index!
Increased refractive-index contrast

Red arrows: Decrease Y and increase Gd and Lu fractions

⇒ Increased index contrast $\Delta n$ up to $1.8 \times 10^{-2}$ between $\text{KY}_{1-x-y-z}\text{Gd}_x\text{Lu}_y\text{RE}_z(\text{WO}_4)_2$ layer and $\text{KY}(\text{WO}_4)_2$ substrate

⇒ Tighter light confinement in thinner layers

Pump/signal wavelengths in Yb$^{3+}$

High inversion in channel waveguides
⇒ exploit large cross-section at central line:

$$\sigma_{em} = 1.15 \times 10^{-19} \text{ cm}^2 \text{ at } 981 \text{ nm}$$

$$\lambda_{pump} = 934 \text{ nm}$$

$$\lambda_{signal} = 981 \text{ nm}$$

Pump-probe-beam experiment

Internal net gain (dB/cm): $g_{mod} = 10 \log_{10} \left( \frac{I_p}{I_u} \right) / \ell - \alpha$

Ratio of pumped vs. unpumped signal intensity $I \Rightarrow$ knowledge of coupling efficiency not needed
Yb$^{3+}$ concentration of 47.5%, excitation fraction of 84.3%  
⇒ expected modal gain

Modal gain in $\text{KGD}_x\text{Lu}_{1-x}(\text{WO}_4)_2:\text{Yb}^{3+}$

Waveguide ($|$|$N_g$):
N.A. = 0.3
height 2.2 µm
etch depth 1.4 µm
width 6 µm
length 180 µm
wedged endfaces
Yb doping 47.5%

Pump/probe exp.:
beams pol. $E || N_m$
Gain:
$G_{\text{mod}} = 17$ dB
$g_{\text{mod}} = 935$ dB/cm

## Device gain: Comparison

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Modal gain in KGd$_x$Lu$_{1-x}$(WO$_4$)$_2$:Yb$^{3+}$

Gain of 150 dB/cm over 55 nm (16.3 THz) range around 1 µm!

Comparison: $\Delta \lambda/\lambda$ (Yb) = 55 nm/1000 nm = 0.055 at 150 dB/cm level

vs. $\Delta \lambda/\lambda$ (Er) = 80 nm/1550 nm = 0.052 at 0 dB/cm level

D. Geskus et al., submitted (2013)
Amplifiers for optical backplanes

Almost 60 dB fiber-to-fiber gain with 1-mm-long amplifier expected!

Y.S. Yong et al., to be submitted (2013)
1. Rare-earth-ion-doped high-gain amplifiers in potassium double tungstates

2. Rare-earth-ion-doped a-Al$_2$O$_3$ narrow-linewidth lasers on a silicon chip

3. Dual-wavelength lasers, microwave generation, and intra-laser-cavity optical sensing on a silicon chip
Rare-earth-doped $\text{Al}_2\text{O}_3$ planar waveguides

Deposition by reactive co-sputtering on thermally oxidized Si

K. Wörhoff et al., IEEE J-QE 45, 454 (2009)

$\Rightarrow$ integration with Si-technology

Microstructurering by chlorine-based reactive ion etching


propagation losses @ 1550 nm

$\sim$ 0.21 dB/cm
Erbium: Energy levels and processes

Simplified Er\(^{3+}\) model (valied only for oxides):

GSA: ground-state absorption
LUM: luminescence
SE: stimulated emission
ETU: energy-transfer upconversion

\begin{align*}
3 &= ^4I_{9/2} \\
2 &= ^4I_{11/2} \\
1 &= ^4I_{13/2} \\
0 &= ^4I_{15/2}
\end{align*}

\begin{align*}
\tau &< 1 \text{ ms} \\
\tau &= 60 \text{ ms} \\
\tau &= 7.6 \text{ ms}
\end{align*}

J.D.B. Bradley et al.,

Cross Section [10^{-21} cm^2]

Wavelength [nm]
Amplifier performance

Without ETU, the Er\textsuperscript{3+} amplifier would be a marvellous tool, producing tens of \text{dB/cm} gain.

With ETU we would choose an Er\textsuperscript{3+} conc. of \(8 \times 10^{20}\ \text{cm}^{-3}\) to achieve \(~7.5\ \text{dB/cm}\) gain.

With quenched ions we are limited to \(~2\ \text{dB/cm}\).

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**Graph:**

- **x-axis:** Er\textsuperscript{3+} concentration (10\textsuperscript{20} cm\textsuperscript{-3})
- **y-axis:** Internal Net Gain (dB/cm)
- **Graphs:**
  - ETU and no fast quenching
  - ETU and fast quenching
  - No ETU and no fast quenching

**Equations:**

- \(\tau_{1q} = 50\text{ns}\)
- \(\tau_{1q} = 1\mu\text{s}\)

**Reference:**

First laser in \( \text{a-Al}_2\text{O}_3: \text{Er}^{3+} \) micro-ring laser

Losses \( \sim 0.2 \) dB/cm, gain \( \sim 2.0 \) dB/cm \( \Rightarrow \) laser possible!

Fast luminescence quenching affects amplifier performance and laser threshold, but not laser slope efficiency

\[ \text{L. Agazzi et al., Appl. Phys. Lett. 100, 011109 (2012)} \]

\( \text{Al}_2\text{O}_3: \text{Er}^{3+} \) micro-ring laser

\[ \text{J.D.B. Bradley et al., Opt. Lett. 35, 73 (2010)} \]
Bragg-grating cavities

Shallow-ridge straight waveguide

Single transverse mode

Mode confinement in waveguide layer >90%

Grating/mode overlap ~0.15%

Low loss: 0.14±0.07 dB/cm (including grating loss)
Bragg-grating fabrication

Laser interference lithography (LIL) → 266 nm laser

Reactive ion etching – CHF$_3$ and O$_2$

488 nm (316 nm) period for 1545 nm (1021 nm) Bragg wavelength

1-cm-long Bragg grating:

~20 000 periods (1545 nm)
~30 000 periods (1012 nm)

E.H. Bernhardi et al., Photon. Nanostruct. 9, 225 (2011)
Bragg-grating characterization

Grating strength $\kappa L = 6.5$

($\kappa$: coupling coefficient; $L$: grating length)

Coupled-mode theory

$\Rightarrow R = \tanh^2(\kappa L)$

Grating length varied from $L = 1.25 - 4.75$ mm

$\Rightarrow R > 99\%$

E.H. Bernhardi et al., Photon. Nanostruct. 9, 225 (2011)
Distributed-feedback cavity with phase shift

Single longitudinal mode: ($\lambda/4$ phase shift required)

Localized adiabatic waveguide widening

Sinusoidal taper
($2.50 \mu m \rightarrow 2.75 \mu m$)

2 mm phase-shift length

Position of phase shift optimized ($0.4 L_{cav}$)


$\frac{L_{ps}}{R} = \frac{\lambda}{2\delta n_{eff}}$

$4 \text{ mm} \quad R = 96.8\%$

$6 \text{ mm} \quad R = 99.7\%$
Distributed-feedback cavity with phase shift

Best passive DFB cavity:

- Linewidth: $\Delta \lambda_c = 1.17 \text{ pm}$
- $\Delta \nu_c = 140 \text{ MHz}$
- $Q$-factor: $Q_c = 1.35 \times 10^6$

$Q = 1.35 \times 10^6$

$E.H.\ Bernhardi\ et\ al.,\ Photon.\ Nanostruct.\ 9,\ 225\ (2011)$
Cavity quality factor $Q_c$ and linewidth

The $Q$-factor of any resonator (be it mechanical, electrical, optical, …) is defined as:
the energy stored in the resonator divided by
the energy lost per oscillation cycle

$$Q_c := 2\pi \frac{E_{\text{stored}}(t)}{E_{\text{lost}}(t)} = 2\pi \frac{\varphi(t)}{\frac{1}{\nu} \frac{d}{dt} \varphi(t)} = 2\pi \frac{\varphi(t)}{-\frac{1}{\nu} \left[ -\frac{1}{\tau_c} \varphi(t) \right]} = 2\pi \tau_c \nu = \frac{\nu}{\Delta \nu_c}$$

$\varphi(t) =$ number of photons in the resonator: 

$$E(t) = h\nu \varphi(t)$$

Fourier transformation $\Rightarrow$ linewidth:

$$\Delta \nu_c = \frac{1}{2\pi \tau_c}$$
Single-frequency Er\textsuperscript{3+} DFB laser

Er\textsuperscript{3+} concentration \textasciitilde3\times10\textsuperscript{20} cm\textsuperscript{-3}

1-cm-long cavity

\lambda_{laser} = 1545.2 \text{ nm}

Low threshold: 2.2 mW
(vs. absorbed pump power)

Slope efficiency: 41.3%
(vs. absorbed pump power)

Output power: 3 mW
(pump-power limited)

Measurement of coherence time

Self-heterodyne experiment:

Coherence lengths:
\[ \ell_c = 3.8 \text{ cm} \]
\[ \ell_L = 56 \text{ km} \]

Line widths:
\[ \Delta \nu_c = 2.5 \text{ GHz} \]
\[ \Delta \nu_L = 1.7 \text{ kHz} \]

\(Q\)-factors:
\[ Q_c = 7.8 \times 10^4 \]
\[ Q_L = 1.14 \times 10^{11} \]
\[ \Lambda = 1.5 \times 10^6 \]

E.H. Bernhardi et al.,
Subsequent work by other research groups

MIT, Cambridge (Watts group)

Purnawirman et al.,

UC Santa Barbara (Blumenthal group)

M. Belt et al.,

SiN channel waveguide with side-relief Bragg gratings and Al$_2$O$_3$:Er$^{3+}$ cladding layer
Single-frequency Yb$^{3+}$ DFB laser

Low threshold: 5 mW
(vs. launched pump power)

Slope efficiency: 67%
(vs. launched pump power)

Output power: 55 mW
(pump power limited)

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Dual-wavelength laser

Two distributed phase shifts in single cavity

⇒ two independent wavelengths

RF beat signal: Improved temp. stability

Temperature stability: \[ \frac{d\nu}{dT} = 2.0 \text{ GHz/K} \]

RF beat signal: Improved temp. stability

Temperature stability:
~3 orders of magnitude improvement!

\[ \Delta f / dT = 2.0 \text{ GHz/K} \]
\[ d(\Delta f) / dT = 0.08 \pm 2.2 \text{ MHz/K} \]

Optical nano-sensing with DFB laser
Scanning DFB laser with microsphere tip

Scanning with an AFM borosilicate microspheres of 1–20 μm diameter over waveguide region

Scanning with AFM microsphere tip

- Scanning microsphere over waveguide region
  ⇒ induces laser scattering loss ⇒ changes laser threshold
  ⇒ changes pump absorption ⇒ changes temperature
  ⇒ changes grating chirp ⇒ changes beat frequency

Intra-laser-cavity nano-particle sensor

Particle sizes down to 1 µm diameter detected

Current detection limit: 500 nm diameter

Stabilize pump power, minimize back reflections, optimize grating geometry to increase evanescent field ⇒ detection down to 10 nm size feasible

ERC Advanced Grant

“Optical Ultra-Sensor” (OPUS): 2.5 MEUR funding

Project goals:
1) Waveguide and grating geometries for low-loss Bragg-grating resonators in Al$_2$O$_3$ for demonstrating on a silicon chip:
2) Ultra-high-$Q$ DFB lasers on a silicon chip ($Q_L = 10^{14}$, $\Delta \nu_L = 1$ Hz, $\ell_{coh} = 10^5$ km, $P_{int} = 1$ kW)
3) Intra-laser-cavity optofluidic sensors
4) Intra-laser-cavity trace-gas absorption sensors
5) Intra-laser-cavity Raman spectroscopy
6) Intra-laser-cavity energy-transfer spectroscopy approaching the single-ion level
Summary

1000 dB/cm peak gain and 150 dB/cm gain over 55 nm bandwidth in Yb-doped potassium double tungstate waveguide

Dual-wavelength, few-kHz-linewidth DFB laser in a-Al₂O₃ on silicon chip, intra-laser-cavity nano-particle sensing