Reinventing the light switch: logic with photons

Christopher C. Evans
University of Massachusetts, Lowell
Lowell, MA, 25 April 2012
and also:

Jennifer Choy
Parag Deotare
Katia Shtrykova

Kasey Phillips
Ruwan Senaratne
Francois Parsy
Grisel Rivera Batista
Stephanie Scwartz

Prof. Erwin Martí-Panameño (BUAP)
Prof. Marco Loncar (Harvard)
Prof. Markus Pollnau (Twente)
Prof. Erich Ippen (MIT)

Prof. Limin Tong (Zhejiang)

Dr. Geoff Svacha
Dr. Rafael Gattass
Prof. Tobias Voss
telecommunication bands

1550 nm
telecommunication bands
1300 and 1550 nm
interconnect band
850 nm
1 all-optical logic
2 NL materials
3 TiO$_2$ photonics
large divergence, small NL interactions

free-space
strong confinement, sustained NL interactions

waveguides
nanowire waveguides

$d = 260 \text{ nm}$
$L = 4 \text{ mm}$

50 $\mu$m

all-optical logic
nanowire waveguide

all-optical logic
nanowire waveguide

all-optical logic
spectral broadening

self-phase modulation: \( n = n_o + n_2 I \)
spectral broadening

self-phase modulation: $n = n_0 + n_2 I$
self-phase modulation: \( n = n_0 + n_2 I \)
spectral broadening

self-phase modulation: \( n = n_o + n_2I \)
spectral broadening

self-phase modulation:  \( n = n_0 + n_2 I \)
strong confinement

\[
S \text{ (a.u.)}
\]

\[
x (\mu m) \quad y (\mu m)
\]

all-optical logic
strong confinement
strong confinement
strong confinement
strong confinement
strong confinement
large evanescent field
high effective nonlinearity

silica fiber at 800 nm

\[ \text{high effective nonlinearity} \]

\[ \text{silica fiber at 800 nm} \]
routing light

1 all-optical logic
all-optical modulation

nanowire Sagnac interferometer

coupling region
all-optical modulation

nanowire Sagnac interferometer
all-optical modulation

nanowire Sagnac interferometer

input

coupling region

cw
all-optical modulation

nanowire Sagnac interferometer

1 all-optical logic
all-optical modulation

nanowire Sagnac interferometer

1 all-optical logic
all-optical modulation

output = transmitted cw + ccw power
all-optical modulation

input electric field amplitude $E_{in}$

![Diagram showing input electric field amplitude $E_{in}$ and coupling region.](image-url)
all-optical modulation

coupling parameter: $\rho$

Diagram:

- $E_{in}$
- $\rho^{1/2}E_{in}$
- Input
all-optical modulation

phase accumulation over path length of loop

\[ E_{\text{in}} \rightarrow \rho^{\frac{1}{2}}E_{\text{in}} e^{i\phi_{\text{cw}}} \rightarrow \rho^{\frac{1}{2}}E_{\text{in}} \rightarrow \text{input} \]
all-optical modulation

coupling parameter: $\rho$

1 all-optical logic
all-optical modulation

output is sum of transmitted cw and ccw
all-optical modulation

accumulated phase:

\[ \phi = k_o n \]
all-optical modulation

accumulated phase:

\[ \phi = k_o n \]

nonlinear index:

\[ n = n_o + n_2 I = n_o + n_2 \frac{P_i}{A_{\text{eff}}} \]
all-optical modulation

accumulated phase:

\[ \phi = k_o n \]

nonlinear index:

\[ n = n_o + n_2 I = n_o + n_2 \frac{P_i}{A_{eff}} \]

nonlinear parameter:

\[ \gamma = n_2 \frac{k_o}{A_{eff}} \]
all-optical modulation

power-dependent output:

\[
\frac{E_{out}^2}{E_{in}^2} = 1 - 2\rho(1 - \rho)\{1 + \cos[(1 - 2\rho)\gamma P_o L]\}
\]
all-optical modulation

power-dependent output:

\[
\frac{E_{out}^2}{E_{in}^2} = 1 - 2\rho(1 - \rho)\{1 + \cos[(1 - 2\rho)\gamma P_o L]\}
\]

for 50-50 coupler:

\[
\rho = 0.5
\]

all-optical logic
all-optical modulation

power-dependent output:

\[ \frac{E_{out}^2}{E_{in}^2} = 1 - 2\rho(1 - \rho)\{1 + \cos[(1 - 2\rho)\gamma P_o L]\} \]

for 50-50 coupler:

\[ \rho = 0.5 \]

no transmission:

\[ \frac{E_{out}^2}{E_{in}^2} = 0 \]
Sagnac interferometer transmission

when $\rho \neq 0.5$:
logic gates

nonlinear nanogate
logic gates

nonlinear nanogate

\[ \rho = 0.45 \]

![Graph showing input power vs. output power for a nonlinear nanogate, with a peak output at \( \rho = 0.45 \).]
logic gates

nonlinear nanogate

\[ \rho = 0.45 \]
logic gates

nonlinear nanogate

![Graph showing output power vs. input power for a nonlinear nanogate with ρ = 0.45. The graph includes a red curve indicating logic "1".]
logic gates

nonlinear nanogate

A
B
 Q

\( \rho = 0.45 \)

0 20 40 60 80 100

logic "1"

\[\begin{array}{ccc}
A & B & Q \\
0 & 0 & 0 \\
\end{array}\]

input power (W)

output power (W)

all-optical logic
logic gates

nonlinear nanogate

logic gates

\[ \rho = 0.45 \]

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

all-optical logic
logic gates

nonlinear nanogate

\[ \rho = 0.45 \]

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

all-optical logic
logic gates

nonlinear nanogate

\[
\rho = 0.45
\]

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

A B Q

logic ‘1’

output power (W)
logic gates

nonlinear nanogate

A
B

\[ \rho = 0.45 \]

A  B  Q

0  0  0
1  0  1
0  1  1

all-optical logic
logic gates

nonlinear nanogate

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Input power (W): 0 20 40 60 80 100

Output power (W): 0 5 10 15 20 25 30 35 40 45 50

logic “1”

all-optical logic
logic gates

nonlinear nanogate

XOR

A  B  Q
0  0  0
1  0  1
0  1  1
1  1  0

logic gates

all-optical logic
logic gates

nonlinear nanogate

\[ \rho = 0.42 \]

\[ \begin{array}{ccc}
A & B & Q \\
0 & 0 & 0
\end{array} \]

[Graph showing input power vs. output power with peaks at 0, 20, 40, 60, 80, 100 W and output power values at 0, 10, 20, 30, 40, 50 W.]

all-optical logic
logic gates

nonlinear nanogate

\[ \rho = 0.42 \]

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

all-optical logic
logic gates

nonlinear nanogate

A
B

\( \rho = 0.42 \)

A B Q

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

all-optical logic
logic gates

nonlinear nanogate

\[ \rho = 0.42 \]

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

all-optical logic
logic gates

for NAND gate need output with no input

\begin{tabular}{ccc}
A & B & Q \\
0 & 0 & 1 \\
\end{tabular}

\begin{tikzpicture}
\node (A) at (0,0) {A};
\node (B) at (1,-1) {B};
\node (Q) at (3,0) {Q};
\draw (A) -- (B) -- (Q);
\end{tikzpicture}
logic gates

for NAND gate need output with no input

A B Q

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

all-optical logic
logic gates

for NAND gate need output with no input

\[
\rho = 0.435
\]

A B Q

0 0 1

all-optical logic
logic gates

universal NAND gate

A B Q
0 0 1
1 0 1
0 1 1
logic gates

universal NAND gate

A B Q

0 0 1
1 0 1
0 1 1

all-optical logic
logic gates

universal NAND gate

A
B
C

\( \rho = 0.435 \)

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

all-optical logic
what about a Gaussian pulse?
dispersion can change the intensity

- modal dispersion
- material dispersion
- waveguide dispersion
engineering dispersion

waveguide dispersion

Optics Express, 12, 1025 (2004)

all-optical logic
engineering dispersion

waveguide dispersion

Optics Express, 12, 1025 (2004)

1 all-optical logic
pulses in a Sagnac
engineering dispersion

waveguide dispersion

all-optical logic
solitons: “light bullets”!

waveguide dispersion

Optics Express, 12, 1025 (2004)
waveguide dispersion

engineering dispersion

![Graph showing waveguide dispersion](image)

- Total dispersion (ns nm$^{-1}$ km$^{-1}$) vs. wavelength (nm)
- Curves for 800 nm and 1200 nm wavelengths
- Peak at 800 nm

Optics Express, 12, 1025 (2004)

all-optical logic
engineering dispersion

waveguide dispersion

![Graph showing waveguide dispersion](image)

- Total dispersion (ns nm \(^{-1} \) km \(^{-1} \))
- Wavelength (nm)
- 600 nm, 800 nm, 1200 nm

Optics Express, 12, 1025 (2004)

all-optical logic
engineering dispersion

waveguide dispersion

![Graph showing waveguide dispersion with wavelengths and total dispersion values.](image)

- 400 nm
- 600 nm
- 800 nm
- 1200 nm

Optics Express, 12, 1025 (2004)

all-optical logic
engineering dispersion

waveguide dispersion

![Graph showing waveguide dispersion with wavelengths from 200 nm to 1200 nm.](image)

- 200 nm
- 400 nm
- 600 nm
- 800 nm
- 1200 nm

Total dispersion (ns nm km$^{-1}$) vs. wavelength (nm)

Optics Express, 12, 1025 (2004)
soliton pulses in a Sagnac
soliton pulses in a Sagnac
soliton pulses in a Sagnac

Input Pulse
Output Pulse

normalized power

time (ps)

0.4

-0.4 -0.2 0 0.2 0.4

all-optical logic
1 all-optical logic
2 NL materials
3 TiO₂ photonics
fast nonlinearities

Boyd, Nonlinear optics, 3rd ed.

1. all-optical logic
2. NL materials
fast nonlinearities

Boyd, Nonlinear optics, 3rd ed.

1 all-optical logic
2 NL materials
fast nonlinearities

Boyd, Nonlinear optics, 3rd ed.

1 all-optical logic
2 NL materials
fast nonlinearities

Boyd, Nonlinear optics, 3rd ed.

1 all-optical logic
2 NL materials
fast nonlinearities

Boyd, Nonlinear optics, 3rd ed.

1. all-optical logic
2. NL materials
fast nonlinearities

![Graph showing characteristic time scale vs. n² (cm²/W) magnitude]

Boyd, Nonlinear optics, 3rd ed.

1 all-optical logic
2 NL materials
fast nonlinearities

Boyd, Nonlinear optics, 3rd ed.
... comparatively small
Linear losses

Energy

Conduction Band

Linear Absorption
(one photon)

Valence Band

1 all-optical logic

2 NL materials
two-photon absorption

Conduction Band

Valence Band

Energy

Two-Photon Absorption

1. all-optical logic
2. NL materials
two-photon absorption limitation

\[ FOM = \frac{n_2}{\beta \lambda} \]


1. all-optical logic
2. NL materials
two-photon absorption limitation in silicon

\[ FOM = \frac{n_2}{\beta \lambda} \]


1 all-optical logic  2 NL materials
two-photon absorption limitation in silicon

\[ FOM = \frac{n_2}{\beta \lambda} \]


1 all-optical logic  
2 NL materials
modeling nonlinearities


1 all-optical logic  2 NL materials
modeling nonlinearities

\[ \frac{hc}{\lambda} < \frac{E_g}{2} \]


1 all-optical logic
2 NL materials
modeling nonlinearities

\[ \frac{hc}{\lambda} < \frac{E_g}{2} \]


1 all-optical logic  2 NL materials
modeling nonlinearities

\[ \frac{hc}{\lambda} < \frac{E_g}{2} \]


1 all-optical logic  2 NL materials
Titanium dioxide (TiO$_2$)
TiO$_2$ material properties

- Large nonlinearity: 30 x silica
- High index of refraction: 2.5
- Wide bandgap: 3.1 eV
- Low two-photon absorption: $\geq$ 800 nm

Several phases: rutile, anatase, brookite and amorphous

1. all-optical logic
2. NL materials
3. TiO$_2$ photonics
deposition: low-loss films

1 all-optical logic
2 NL materials
3 TiO₂ photonics
planar waveguide

Air

TiO$_2$ $n = 2.4$

SiO$_2$ $n = 1.45$

Silicon

1 all-optical logic  2 NL materials  3 TiO$_2$ photonics
1 all-optical logic  
2 NL materials  
3 TiO$_2$ photonics
nano-scale structuring

TiO$_2$

Silica

1. all-optical logic
2. NL materials
3. TiO$_2$ photonics
visible light propagation

straight rib waveguides

1 all-optical logic  2 NL materials  3 TiO$_2$ photonics
amorphous waveguides

200 μm

λ = 780 nm

1 all-optical logic
2 NL materials
3 TiO₂ photonics
anatase waveguides

1. all-optical logic
2. NL materials
3. TiO$_2$ photonics

$\lambda = 780$ nm

200 um
microbends

100 µm

r = 20 µm

1 all-optical logic  2 NL materials  3 TiO₂ photonics
microbends

\[ r = 20 \, \mu m \]
variable splitters

1. all-optical logic
2. NL materials
3. TiO₂ photonics
variable splitters

1 all-optical logic
2 NL materials
3 TiO$_2$ photonics
variable splitters

1. all-optical logic
2. NL materials
3. TiO$_2$ photonics
more complex devices

1 all-optical logic
2 NL materials
3 TiO$_2$ photonics
more complex devices

1 all-optical logic
2 NL materials
3 $\text{TiO}_2$ photonics
the first nonlinear optics in TiO$_2$
the first nonlinear optics in TiO$_2$
the first nonlinear optics in TiO$_2$
the first nonlinear optics in TiO$_2$

![Graph showing normalized power (dB) vs. wavelength (nm) with data points at 740, 780, 820, 860 nm. The graph includes curves for 1 pJ, 7 pJ, and 28 pJ.]
the first nonlinear optics in TiO$_2$

![Graph showing normalized power against wavelength for different pulse energies: 1 pJ, 7 pJ, 28 pJ, and 46 pJ. The x-axis represents wavelength in nm, and the y-axis represents normalized power in dB. The graph highlights the response of TiO$_2$ to different pulse energies.]
the first nonlinear optics in TiO$_2$

\[ \Upsilon \sim 40 \text{ W}^{-1}\text{m}^{-1} \]

(\sim 40,000 \times \text{silica fiber})
the first nonlinear optics in TiO$_2$

up to 4x stronger anomalous dispersion than silica nanowires
... spanning the communications octave!

\[ \Upsilon \sim 10 \text{ W}^{-1}\text{m}^{-1} \]

(10,000x silica fiber)
1 all-optical logic  
2 NL materials  
3 TiO$_2$ photonics
Summary

switching photons with photons

introduced a novel material
Summary

switching photons with photons

introduced a novel material

... close to the first nonlinear Sagnac in TiO$_2$
Funding:

National Science Foundation
Nanoscale Science and Engineering Center
Harvard Quantum Optics Center
Department of Energy

for more information and a copy of this presentation:

http://mazur.harvard.edu

Follow me! eric_mazur