Technologies for Optical Processing

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Tutorial OFC 2008

Technologies for Optical Processing

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- M.L. Nielsen, NEC
- M.K. Smit, E. Tangdiongga and H.J.S. Dorren, TU/e
- D. Blumenthal, UCSB

Dream of the optical transistor

Why?

- Keeping signals in the optical domain
- Small losses in transmission
- Long term: excessive processing capacity

Important factors

- Size/compactness
- Switching energy
- Switching time
- Wavelength
- Cost

Contents

- Application areas
- Types of nonlinear gates
 - Semiconductor optical amplifier (SOA)
 - Interferometers and cavities
 - Fibers and waveguides
- All-optical logic and flip-flops
- Towards ultra compact and single photon transistors

WDM cross connects

Key components:

- Switches
- Demuxes
- Wavelength converters

Optical Time Division Multiplex Systems

Key components:

- Pulse sources
- Demuxes
- Add/drops

Optical packet switching networks

Key components:

- Switches
- Wavelength converters
- Header processing (All-optical)
- Simple optical logic

Optical computer (into the future?)

Key components:

- Optical interconnects
- Massive all-optical logic

OMV1.pdf

Electronic switching

DTU

$$U = \frac{1}{2} CV^2$$

1 fJ/switching event

Number is much larger on chip because every wire is also a capacitor;
The energy for an "average" switching event is likely to be 10-100 fJ.

After TF Krauss, <http://www.cfn.uni-karlsruhe.de/web/>

Simple functions with all-optical gates

Cross Gain/(Absorption) Modulation (XGM)

Cross Phase Modulation (XPM)

Four wave mixing

Semiconductor optical amplifier (SOA) as nonlinear gate

Tested technology

Large band-filling nonlinearity ($n_2 \sim 10^6 \times$ silica fiber)

Switch powers $< 100\text{fJ}$

Switching time is an issue

Requires bias of 10-100 mA

Compact (mm size) and compatible with photonic integration

Numerous experimental results

Amplification and saturation in an SOA

Saturation allows control of light with light –
but at which speed ?

SOA dynamics – patterning effects

Cross-gain modulation for wavelength conversion:

Patterning effect: energy in time slot depends on previous bits

Notice: The phase is modulated analogously through XPM

J. Moerk and M.L. Nielsen, COM

Another configuration – the DISC

This configuration may be viewed in general as an SOA followed by an external filter:

Bandwidth enhancement using optical filtering

J. Moerk and M.L. Nielsen, COM

Effect of filtering

Normalized response at input:

$$T_{CDP}(\Omega) = \frac{p_p(\Omega)}{p_p(0)} = \frac{1}{1 - j\Omega\tau_s} \rightarrow H(\omega) \rightarrow T_{tot}(\Omega) = \frac{p_{out}(\Omega)}{p_{out}(0)} = T_H(\Omega)T_{CDP}(\Omega)$$

Normalized response at output:

Transfer function for AMZI:

τ : Period of transfer function
 Φ_0 : Translates transfer function

See e.g., M.L. Nielsen et al.,
 Opt. Exp., Vol. 14, No. 3,
 February 2006.

J. Moerk and M.L. Nielsen, COM

160 Gb/s All-Optical Operation

A 160 Gb/s 3R all-optical wavelength conversion.
 Required input power lower than -2 dBm.
 Regeneration for degraded input signals.

Ref.: J. Leuthold et al., to be published in *El. Lett.*, 2004
 Courtesy of M. Renaud

OMV1.pdf

Differential control scheme (S. Nakamura, 1994)

Slow carrier recovery effects removed
↓
short switching window

Mach-Zehnder Interferometer

Flip-chip mounted MZI-SOA

H. Melchior et al., ETH-Zürich
Mid-90's

Ultra high-speed optical signal proc. w. MZI type switch

Fig. 1. Hybrid-integrated Symmetric Mach-Zehnder all-optical switch

Fig. 2. 336-Gbps demultiplexing with HI-SMZ switch.
(a) Cross-correlation trace of input signal pulses.
(b) Results of BER measurement.

Nakamura, Ueno and Tajima, NEC
IEEE LEOS Summer Topical meeting, 2004

2-stage Push-Pull MZI wavelength converter

J.A. Summers et al., Photn. Techn. Lett., Vol. 19, No. 21, p. 1768, Nov., 2007

3R-regenerator with cascaded gates

Fig.5 : Eye diagram evolution in the cascade after de-multiplexing at 10 Gbit/s.

200 regenerators at 20 Gbit/s, transmission ~22.000 km

B. Lavigne et al., OFC2000, paper ThF7, 2000

Other interferometric gates

Patel et al. (MIT), Photon. Techn. Lett., vol. 8, pp. 1695-1697, 96

Sokoloff et al. (Princeton), Photon. Techn. Lett., vol. 5, pp.787-790, 93.

Quantum confinement

Engineering materials with unique properties:

1. Enhanced interaction with light for more efficient device operation.
2. Reduced scattering for faster dynamics (GHz→THz).
3. Better wavelength control and short pulse propagation (chirp effects).

Kristjan Leosson

Signal processing in QD SOAs

- Long device (4 mm)
- 20dB gain
- 1 pJ input pulses
- 1 ps pulses
- 1 ps capture
- Worst case signal

Berg et al., CLEO'02
Sugawara et al. JJAP, '01
 Exp. Demo @ 40 Gb/s:
Akiyama et al., ECOC'02

SHB – fast recovery (capture time)
Fully inverted QDs and large reservoir – small patterning

J. Moerk and M.L. Nielsen, COM

Photonic crystals and quantum dots

Rise and fall times ~ 2 ps,
switching energies of control pulse as low as 100 fJ.

Asakawa et al., New J. Physics (2006)

All-optical intersubband switching

Optical transitions in QW

Recently: CdS/ZnSe)/BeTe
achieved < 7 pJ switching
energy at 1520 nm

G.W. Cong et al., Opt. Exp.,
10 Sept. 2007, Vol. 15, No. 19

DBR-laser converters

Nano/micro cavity lasers

Fibers and waveguides as nonlinear elements

Fibre switches:

Kerr effect $\chi^{(3)}$ non-linear phase shift: $\phi \sim \gamma PL$,
caused by molecular vibrations ~ 5 fs response
time

Typical control pulse (5ps FWHM at 10 GHz):
50 mW average switching power ~ 1 W peak
power for commercially available HNLF ($\gamma \sim 10$,
 $L \sim 500$ m)

Wavelength conversion in Highly Nonlinear Fibers by Raman-assisted XPM

Raman-assisted XPM-based λ -conversion at 160 Gb/s:

- XPM creates sidebands on cw
- Notch-filter suppresses cw and one sideband,
- Bandpass filter removes data
- Raman-effect increases OSNR

Michael Galili et al, *OFC 2006*

L. Oxenloewe

Photonic crystal fibre demultiplexer

First 160 to 10 Gbit/s error free demultiplexing with PCF^{1,2}
Strong confinement $\rightarrow$ high- γ ($18 \text{ W}^{-1}\text{km}^{-1}$) $\rightarrow$ short fibre: 50 m

- 1: L.K. Oxenløwe et al, *OECC 2002*, paper PD-1-4,
2: L.K. Oxenløwe et al, *ECOC 2003*, paper Th2.5.3 16E3-5

L.K. Oxenløwe

640 Gbit/s demultiplexing

Error free 640/10 Gb/s: clear and open eyes

J. Seoane et al, *ECOC 2004*, paper We1.5.4.

L.K. Oxenløwe

Nano-waveguides

Efficient FWM conversion

K. Yamada, IEEE Photon. Techn. Lett., Vol. 18, NO. 9, p. 1046, 2006

For extensive theoretical treatment of nonlinearities in Silicon waveguides see Q. Lin et al., Opt. Exp., 10 Dec. 2007, Vol. 15, No. 25.

All-optical control on Si chip

~500 ps switching time
25 pJ control pulses

V.R. Almeida et al., NATURE, Vol. 431, p. 1081, Oct. 2004

All-optical switching in photonic crystal

Concept based on Kerr nonlinearity

M.F. Yanik et al., OPTICS LETTERS,
Vol. 28, No. 24 / December 15, 2003

Chalcogenide glass

- Effective Area: $\sim 5\text{--}7\ \mu\text{m}^2$, $n_2=110\times\text{silica}$
- $\gamma=1700\text{--}2000\ \text{W}^{-1}\text{km}^{-1}$
- Insertion loss $\sim 6\ \text{dB}$

<http://www.cudos.org.au/cudos/meetings/Astrophotonics/>

160-Gb/s Optical Time-Division Demultiplexing by
Four-Wave Mixing

M. D. Pelusi et al., PTL, vol. 19, NO. 19, Oct., 2007

40 Gb/s wavelength conversion by XPM

M.R.E. Lamont et al., Opt. Exp., Vol. 15, No. 23, Nov. 2007

Nonlinear optical properties of third-order nonlinear materials @ $\lambda = 1.5 \mu\text{m}$.

Material	n_2 [$\times 10^{-20} \text{ m}^2/\text{W}$]	α_2 [10^{-12} m/W]	FOM
Chalcogenide glass (As_2S_3)	290	<0.01	>10
Chalcogenide glass (As_2Se_3)	1200	1	2
Bismuth Oxide (Bi_2O_3)*	110	-	-
Silicon (Si)	440	8.4	0.4
Silica (SiO_2)*	2.2	-	-

Vahid G. Ta'eed et al., Opt. Exp., Vol. 15, No. 15, 23 July 2007

Silicon-on-insulator waveguides w. nonlinear cover

Material	$\text{Re}\{\gamma\}/(\text{W m})^{-1}$			λ/nm	n_0	$n_2/(\text{m}^2/\text{W})$	FOM _{TPA}	Ref.
	TM _{strip}	TE _{strip}	TE _{slot}					
Inorganic materials								
Pure silica glass	0.3	0.5	1.0	1550	1.45	2.48×10^{-20}	$\gg 10$	[15]
Lead silicate glass								
Schott SF59	8.0	11	17	1060	1.91	6.8×10^{-19}		[25]
Bismite glass	3.5	4.4	6.9	1550	2.02	3.2×10^{-19}		[26]
Tellurite glass								
$\text{Li}_2\text{O-TiO}_2\text{-TeO}_2$	6.2	7.5	11	1900*	2.2	6.53×10^{-19}		[27]
Chalcogenide glass								
$\text{As}_{24}\text{S}_{38}\text{Se}_{38}$	74	86	120	1600	2.45	1.0×10^{-17}		[28]
$\text{As}_{39}\text{Se}_{61}$	71	82	105	1500	2.81	1.6×10^{-17}	3.8	[29]
$\text{As}_{40}\text{Se}_{60}$	102	117	151	1500	2.81	2.3×10^{-17}	11	[29]
Organic materials								
PDA	54	92	186	1319	~ 1.5	4.8×10^{-18}	1.5	[30,31]
PTA	22	38	78	1907*	1.5	2×10^{-18}		[23]
TFE	17	29	58	1907*	1.5	1.5×10^{-18}		[32]
PSTF66	31	54	109	1550	1.5	2.8×10^{-18}	0.22	[33,34]
DANS	94	149	293	1319	1.57	8×10^{-18}	7.6	[35]
PTS (PDA)	2720	3820	6950	1600	~ 1.7	2.2×10^{-16}	>27	[36,37]
Nanocomposites								
Si nanocrystals	22800	33100	61600	813	1.66	1.86×10^{-15}	5.6	[38]
	1120	1910	4000	1500	1.5	$\sim 10^{-16}$		[7]

C. Koos et al., Opt. Exp., Vol. 15, No. 10, 14 May 2007.

Fast waveguide with polymer cover

THz modulation speeds predicted

Michael Hochberg et al., Nature Materials. Vol. 5, p. 705, Sept. 2006

Second harmonic generation in PPLN with QPM

Sunao Kurimura et al., Appl. Phys. Lett. 89, 191123 (2006)

LiNbO₃ has very high $\chi^{(2)}$ but dispersion and birefringence cause beam walk-off. Solution: periodically-poled LiNbO₃

For an overview of $\chi^{(2)}$ nonlinearities see
C. Langrock et al., JLT, Vol. 24, p. 2579, July 2006

Experimental set-up for $\chi^{(2)}$ sum-frequency generation for CR

Soliton compression in fibre w. gain $\rightarrow$ tuneable FWHM: 400-1100 fs

Loop length $\sim$ 43 m + EDFA, but loop filter b.w. $\sim$ 200 kHz $\rightarrow$ ok

L.K. Oxenloewe et al, submitted for Electronics Letters

L.K. Oxenloewe

Switching/Demux highlights from literature - I

- 640 to 10 Gbit/s using XPM in NOLM ¹ (1.28 Tb/s IM+pol-MUX)
- 640 to 10 Gbit/s using Kerr switching with parametric amplification ²
- 640 Gbit/s in NOLM ³ COM
- 640 Gb/s ⁴ (2.56 Tb/s DQPSK + pol-MUX) - Weber
- 500 to 10 Gbit/s using FWM ⁵

Fibres fastest – but – stability of lengthy fibres?

1: M. Nakazawa, et al, *Electron. Lett.* 34 (9) 1998. 2: S. Watanabe et al, *ECOC 2004*, paper Th4.1.6. 3: COM 4: Weber et al, *Electron. Lett.* 42 (3) 2006. 5: T. Morioka et al, *Electron. Lett.* 32 (9) (1996). TuH6.

L.K. Oxenloewe

Switching/Demux highlights from literature - II

Semiconductor switches

- 336 to 10.5 Gbit/s using SOA based Mach-Zehnder interferometer ⁶
- 160 to 10 Gbit/s applying voltage control signal to EAM ⁷
- 160 to 10 Gbit/s using XAM in an EAM ⁸
- 320 to 10 Gbit/s integrating ultra-fast photodiode and EAM ⁹
- 640 to 10 Gbit/s using fa-XPM in an SOA ¹⁰

Alternative switches

- 160 Gbit/s demux in chalcogenide waveguide ($\chi^{(3)}$) X, CUDOS
- 640 Gbit/s clock recovery with PPLN QPM-device ($\chi^{(2)}$) XX, COM, ENST, NIMS,
- 160 Gbit/s demux in chalcogenide waveguide ($\chi^{(3)}$) X, CUDOS

Semiconductors slow – but – integration offers stability

Alternative switches fast – but – loss, dispersion

⁶: S. Nakamura et al, *OFC 2002*, paper FD3-1. ⁷: H. Chou et al, *OFC 2003*, paper ThX2. ⁸: L. Xu et al, *ECOC 2004*, paper We1.5.3. ⁹: S. Kodama et al, *OFC 2003*, paper ThX5. ¹⁰: E. Tangdiongga et al, *PTL 18 (8) 2006* **640 G DEMUX W FA-XPM**, X: M.D. Pelusi, *ECOC-2007/PTL*, XX: L.K. Oxenløwe et al, submitted to *Electronics Letters*

L.K. Oxenløwe

Switch comparison

Type	Switching energy	Timescale	Principle of operation/comments
Transistor	Switch: 1 fJ Circuit: 10 pJ	Sub-ns	CMOS electronic/digital. Extremely small footprint. Transport more power-hungry than actual switching action.
Nonlinear directional coupler	<1 nJ	fs	All-optical, analog switch. Ultra fast (Kerr effect). "Classical" nonlinear optics.
SOA-gate + filter	~ 1-10 fJ	ps	Requires bias. Precise wavelength adjustment
SOA-MZI	100 fJ	ps	Requires bias.
Intersubband abs. switch	5-10 pJ	ps	

Modified after TF Krauss, <http://www.cfn.uni-karlsruhe.de/web/>

Switch comparison cont.

Type	Switching energy	Timescale	Principle of operation/comments
Transistor	Switch: 1 fJ Circuit: 10 pJ	Sub-ns	CMOS electronic/digital. Extremely small footprint. Transport more power-hungry than actual switching action.
Nonlinear fiber	1-10 pJ	fs	Long length require stable packaging.
PC laser cavity	50-100 fJ	ps	Precisely adjusted wavelength
Dual ring flip-flop	5 fJ	ps	Digital. Injection locking of CW/ACW modes. Large bias (10's of mA) required
Micro ring	10 fJ	ns	Analog. Carrier injection.

Modified after TF Krauss, <http://www.cfn.uni-karlsruhe.de/web/>

Switching Power-Delay Characteristics

O. Wada, FESTA

The principle of XOR in an IWC

Tina Fjelde

40 Gbit/s all-optical XOR gate

R.P. Webb et al., *Electron. Lett.* Vol 39 No. 1, 2003

All-Optical 40-Gb/s Packet Routing using two UNI-gates

J.P. Wang et al., PTL, Vol. 18, NO. 21, p. 2275, Nov., 2006

All-optical header processing

M.T. Hill et al., Electron. Lett., p. 774, 2001

All-Optical Flip-Flop based on Coupled Ring Lasers

- Continuous lasing for 16 & 12 μm diameter
- Threshold current $\sim 5\text{mA}$

M.T. Hill et al, Nature 432, 206-209 (2004)

Courtesy of H. J. S. Dorren, TUE

Experimental Results

- Pulsed current operation for devices with $\sim 1\%$ coupling to waveguide (coupling introduced 50% loss)
- Achieved bistability, 10-90% transition time $< 18\text{ ps}$, 5.5 fJ switch pulse energy
- Switching with 2fJ also possible

M.T. Hill et al, Nature 432, 206-209 (2004)

Courtesy of H. J. S. Dorren, TUE

Micro and Nanolasers for digital photonics

Coupled two-port resonant tunneling filter

A. Shinya et al., Opt. Exp., Vol. 14, No. 3, February 2006

Levels of reflection and isolation between input-output a challenge

Martin T. Hill, in Proc. of ECIO, paper WC0, Copenhagen Denmark April 2007

OITDA Technology roadmaps

Lithographically controlled, seeded nanowire growth of photonic crystals & other 2D arrays

Thomas Mårtensson,
Nanotechnology 14, 1255 (2003)

Plasmonic interaction

<http://www.neci.nj.nec.com/homepages/thio/>

John Pendry, *Science* 1999
September 10; 285: 1687-1688

Integrated optics using surface plasmon polaritons

Metal thickness:
~ 15 nm

R. Charbonneau, et. al.,
Optics Express 13,
977 (2005)

A. Boltasseva, et. al., *J.*
Lightwave Technol.
23, 413 (2005)

Control of propagation and dispersion by structuring of metal

Alexandra Boltasseva, COM

Single Photon Transistor

Single photon generation and non-linear optics with surface plasmons
Chang, Sørensen et al., *Nature Physics* Vol. 3, p. 807, Nov. 2007

1. Store "gate photon" using classical field ($P \approx 90\%$)
2. "Signal photons" transmitted if gate photon present

Anders S. Sørensen, Niels Bohr Inst., Univ. of Copenhagen

Conclusions

Nonlinear elements based on SOA, fibers and waveguide structures have capabilities of simple processing at data rates of 100-600 Gb/s

- Switching powers comparable to electronics
- No clear preference for technology at this point of time

Higher packing density needed in future systems

Fast progress in highly nonlinear engineered materials

Photonic Bandgap Structures and nano-waveguides have potential for more compact photonic circuits - but more work needed

Conclusions cont.

Nanostructures in switching at the very beginning
Plasmons may be useful for more compact photonic signal processing elements
More experiments needed

Exciting new technologies
Closer to fundamental limits
Engineering of material properties