High-Speed, Low-Power Optical Modulators in Silicon


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ABSTRACT

Silicon modulators are maturing and it is anticipated that they are going to substitute state-of-the-art modulators. We review current silicon modulator approaches and then discuss the silicon-organic hybrid (SOH) approach in more detail. The SOH approach has recently enabled the operation with an energy consumption of 60 fJ/bit and demonstrated the generation of up to 112 Gbit/s per polarization in a compact silicon modulator of 1.5 mm length.

1. INTRODUCTION

Silicon photonics is in the focus of the integrated optics community for the last 10 years. Silicon photonics has the potential to become the major platform for integrated optics. This is due to a number of compelling reasons. So for instance, silicon offers low losses in the important telecommunications window around 1550 nm [1, 2], and it offers compact integrated optic structures with narrow strip waveguides and tight bend radii due to a high refractive index at said telecommunications window [3]. The silicon technology itself is a mature technology that offers a high yield with the potential to combine photonics and electronics on a CMOS compatible platform [4]. The CMOS compatibility gives a scaling advantage when a high device count is needed, and the maturity of the technology has it that quite a few foundries already offer fabless production [5]. To this day, a wealth of passive and active devices has already been implemented [6]. The challenge though is the fabrication not only of compact modulators, but of modulators that are fast and offer low power consumption in combination with high extinction ratios.

In this review we first have a look at current silicon modulation concepts and configurations, and then discuss in more depth the so-called silicon-organic hybrid (SOH) approach. We show how this approach provides ultra-compact silicon modulators with lengths below 1.5 mm and operation voltages in the order of 1 V.

2. PHASE-MODULATION CONCEPTS IN SILICON

Quite a few different electro-optical modulation concepts have been demonstrated in silicon. So far the successful concepts may be roughly classified into three categories.

- **Plasma Dispersion Effect in Silicon**: Quite a few groups are focusing on exploiting the plasma dispersion effect [7], where carriers are either injected by forward biasing a pin-diode that happens to form the photonic waveguide as well [8] or carriers are depleted by reverse biasing the pin-junction within the waveguide [9]. With such solutions on-off-keying (OOK) at data rates up to 50 Gbit/s [10] or 28 GBd in a dual polarization configuration for 16QAM have been demonstrated [11]. Increasingly, more refined structures are suggested. Recently, a so-called silicon-insulator-silicon capacitor configuration (SIS-CAP) structure was reported. With this configuration operation at 28 GBd was demonstrated in a 1 mm long configuration with a VπL product of 2 Vmm. A challenge when exploiting the plasma effect is the fact that plasma dispersion is usually accompanied with plasma absorption. Thus, the larger the phase-shift the more light will be absorbed. This makes it more difficult to generate complex modulation formats.

- **Linear-Electro Optic Effect in Silicon**: A completely different class of silicon modulators makes use of the linear electro-optic effect (Pockels effect). Since the silicon crystal has inversion symmetry it does not come with a linear electro-optic effect. However, by growing strained silicon layers, and thereby breaking the centro-symmetry of crystalline silicon, a linear electro-optic effect was found [12, 13]. More recently, a linear electro-optic effect based on a chemical surface-activation was demonstrated with an estimated value of $\chi^{(2)} = 9 \pm 1$ pm/V for the induced nonlinearity. [14].
**Linear-Electro Optic Effect in Cladding:** In the so-called silicon-organic hybrid (SOH) approach a conventional silicon-on-insulator waveguide is functionalized with an organic cladding material [15, 16]. This way critical fabrication steps can rely on high-yield processes based on CMOS fabrication technology of a silicon-on-insulator (SOI) wafer. The functional organic material can subsequently be deposited onto the wafer. Typical organic cladding materials may be highly-nonlinear \( \chi^{(2)} \) chromophores [17, 18] for high-speed modulation [19] and difference-frequency generation [20], or liquid-crystals for low-voltage phase-shifters [21]. All three effects offer sufficiently fast modulation. The plasma effect though is limited by the lifetime of the charge carriers. In order to keep the plasma effect fast carriers are normally removed by applying a reverse biased field.

### 3. TRAVELLING WAVE OR LUMPED ELECTRODE APPROACH

Speed and power efficiency is also affected by the electrical contact. Two approaches are common:

- **The travelling wave modulator**, see Fig. 1(a), typically needs an electrical termination matched to the wave impedance in order to avoid reflections of RF waves that would interfere with the signal of the next bit. When a matched termination is used, the total power launched into the modulator is dissipated – in part by RF loss and capacitive loading, but eventually in the terminating resistor \( R = 50 \, \Omega \). The voltage amplitude across the modulator input terminal is \( U_0 / 2 \). For a DC-free rectangular drive voltage with a peak-to-peak open-circuit value \( 2U_0 \), representing an alternating series of logical ones and logical zeros with a bitrate \( B \), the energy consumption per bit can thus be approximated by

\[
W_{\text{bit}} = \left( \frac{2U_0}{2} \right)^2 / R / B.
\]

Travelling wave modulators allow fast modulation if they are designed without any walk-off between electrical and optical signals [22].

- **Lumped terminated & unterminated modulator:** Lumped modulators are short and can be operated without terminating resistor. Many resonant modulator configurations are lumped modulators and are usually operated without termination. Examples are slow-light structures [23, 24] or ring resonators [25, 26]. Short non-resonant modulators can also be operated without termination [27]. As an additional advantage of the unterminated lumped modulator, the in-device modulation voltage (the voltage made available at the electrodes of the device) is about \( U_0 \), i.e., it nearly doubles as explained in Fig. 1(c) as compared to the terminated case, Fig. 1(b). The energy consumption of the modulator is then dominated by the capacitive load of the slot waveguide. For the lumped device, we estimate the power dissipation associated with charging and de-charging the total modulator capacitance \( C_{\text{MZM}} = 2 C_{\text{PM}} \) as seen by the coplanar waveguide (CPW) to be

\[
W_{\text{bit}} = C_{\text{MZM}} \times U_{\text{drive}}^2 / 4.
\]

This again assumes equal probabilities of logical ones and zeros, and it takes into account that only transitions consume energy.

![Figure 1](image_url)

**Figure 1.** Equivalent circuit models of various modulator types. (a) Traveling-wave modulator. (b) Simplified model of a terminated lumped modulator. The drive voltage \( U_0 / 2 \) across the modulator input terminals is half the open-circuit source voltage \( U_0 \). The total RF power is dissipated by capacitive loading and by the \( 50 \, \Omega \) termination. (c) Simplified model of an unterminated lumped modulator. The on-chip drive voltage \( U_0 \) equals the open-circuit voltage of the source. Power dissipation inside the modulator is dominated by capacitive loading. Residual power is reflected back to the source.

As an illustrative example, we recently characterized a 10 Gbit/s on-off keying SOH-modulator in a MZI configuration of 1.5 mm length with an 80 nm wide slot and \( V_\mu L \) product of 3.0 V mm [27]. The modulator can be operated in two ways:

- First, we operate the device with a \( 50 \, \Omega \) termination and use a peak-to-peak drive voltage \( U_{\text{drive}} \) of 800 mVpp (i.e., an amplitude of 400 mVp). The voltage \( V_\mu \) which is needed to switch a MZI modulator from minimum to maximum transmission was found to be 2.5 Vpp for high data rates. However, also smaller voltages suffice to get a clear and open eye. In our experiment the energy per bit thus was only 320 fJ when driving the modulator with 800 mVpp.

- Since the device was short and the bit-rate was chosen to be low, operation without a termination is possible. At this data rate the modulator acts as a lumped device. The capacitance of the MZI modulator was found to be \( C_{\text{MZM}} = 2 C_{\text{PM}} = 378 \, fF \), which resulted in an energy consumption of 60 fJ/bit.
4. OPTICAL WAVEGUIDE STRUCTURE AND INTERFEROMETER CONFIGURATION

The optical waveguide structure ultimately determines the performance of the modulator. It needs to be designed such that both the electrical and optical field are guided with a maximum overlap. Ideally, the applied voltage across the optical waveguide drops off within the optical waveguide such that the electrical field is highest.

For the realization of an efficient modulator within the silicon-organic hybrid approach we have decided for a strip-loaded slot waveguide structure, see Fig. 2(a). There are other structures that work well also [15], but the strip-loaded slot approach combines most of the advantages. In this approach the conductive silicon strip-loads connect the two rails of the slot waveguide with metal electrodes [15, 23]. Since the slot is typically only 100 nm wide, and both electrical and optical mode almost ideally overlap in the narrow slot, low voltages only are needed to induce a very high refractive index change in the nonlinear material of the slot. The structure has to be engineered for low losses, though. Unfortunately, the carriers of the doped strip-loads typically add to optical losses through free carrier absorption (FCA). For making the silicon strips sufficiently conductive without causing excessive optical losses it has been suggested to use gate-induced accumulation layers instead of ion-implantation [19].

To encode amplitude and phase on an optical signal we choose an IQ-interferometer configuration as depicted in Fig. 2(b).

5. IQ MODULATOR PERFORMANCE

Finally, we demonstrate the performance of a recently published IQ modulator fabricated on the SOH platform. We show operation at 28 GBd with bit-rates up to 112 Gbit/s and extinction ratios of 26 dB. The device is 1.5 mm long and has a $V_n L$ product of 3.5 Vmm. This allows operation with an energy consumption of 640 fJ/bit. An in-depth description of both the structure and the experiment can be found in Ref. [28].

The frequency response of the modulator is shown in Fig. 3(a). The magenta line shows the frequency response of the modulator with an equalization of the frequency response in the receiver. A 3dB bandwidth of 21 GHz has been found. The blue line shows the frequency response of the modulator. It can be seen that the frequency response at first drops off sharply but then becomes extraordinarily flat towards higher frequencies. This flat response is in part responsible for the good performance at higher speed. The receiver transfer function for flattening the overall frequency response is separately plotted as a red curve in Fig. 3(a) as well, and undoes the drop off of the frequency response at higher frequencies.

Finally, Fig. 3(b) shows the constellation diagram of a QPSK signal generated with the SOH modulator at a symbol rate of 28 GBd. This corresponds to a 56 Gbit/s signal. No equalization was used when these constellations were recorded. The symbols have a clear and distinct shape. The EVM was found to be 14.2% and
bit-error ratios are well below the detection limit of our setup. The constellation diagram in Fig. 3(c) shows how a 16-QAM signal can be generated with equalization at 28 GBD which corresponds to 112 Gbit/s. The symbols are round and distinct indicating a good signal quality. Measurements confirm that we are below the hard-decision FEC limit with a BER of $1.2 \times 10^{-4}$.

6. CONCLUSIONS

We review current silicon modulator concepts and discuss them with respect to speed and power consumption. We show that the silicon-organic hybrid approach offers a platform for ultra-compact modulators. We demonstrated operation from 10 GBD up to 28 GBD with an energy consumption of 60 fJ/bit at 10 GBD up to 640 fJ/bit at 112 Gbit/s [27, 28].

Acknowledgements

We acknowledge support by the EU-FP7 project SOFI, the BMBF joint project MISTRAL, the DFG Center for Functional Nanostructures (CFN), the Helmholtz International Research School on Teratonics (HIRST), the Karlsruhe School of Optics and Photonics (KSOP), and the Karlsruhe Nano-Micro Facility (KNMF).

References

ICTON 2013
Cartagena, Spain
June 23-27, 2013

15th International Conference on Transparent Optical Networks

Co-located with:

- 12th European Symposium on Photonic Crystals (ESPC)
- 12th Workshop on All-Optical Routing (WAOR)
- 10th Anniversary Global Optical & Wireless Networking Seminar (GOWN)
- 9th Reliability Issues in Next Generation Optical Networks Workshop (RONEXT)
- 9th Photonic Integrated Components & Applications Workshop (PICAW)
- 8th Nanophotonics for All-Optical Networking Workshop (NAON)
- 8th Special Session on Photonic Atoms & Molecules (PAM - former MPM)
- 8th Special Industrial Session
- 7th Special Session on Novel Glasses for photonic devices
- 6th Special Session on Market in Telecommunications (MARS)
- 5th COCONUT Workshop on Broadband Access (former ACCORDANCE)
- 5th Sub-Wavelength Photonics Conference (SWP) with:
  - EU FP7-REGPOT Project Special Session on “Plasmon Enhanced Diffractive Elements”
  - Special Session on “Nanophotonics and Smart Optical Nanostructures” (NSON)
- 4th Workshop on Communication in Transportation Systems (CTS)
- 3rd Workshop on Green Optical Communications (GOC)
- 3rd Special Session on Intelligent Systems for Optical Networks Design (ISOND)
- 2nd Special Session on Microwave Photonics (MP)
- 2nd Optical Wireless Workshop (OWW)
- EU FP7 Projects SOFT/NAVOLCHI Special Session on “CMOS Fabrication-Based Photonic Technologies for Communications”
- EU FP7 Projects ASTRON/FOX-C Special Session on “Physical Layer Technologies for Flexible/ Elastic Optical Networks”
- Workshop on “How to Create a Photonic SME”
- Workshop on Network Optimization (NeO)

Welcome

The National Institute of Telecommunications, Department of Transmission and Optical Technologies in Warsaw, together with the Department of Information Technologies and Communications of the Universidad Politécnica de Cartagena, and the IEEE Photonics Society Poland Chapter are pleased to announce the 2013 15th International Conference on Transparent Optical Networks (ICTON 2013) which will be kindly hosted at the El Batel Auditorium and Convention Center, Cartagena, Spain, June 23-27, 2013. The conference is technically co-sponsored by the IEEE and the IEEE Photonics Society.

The El Batel Auditorium is located next to the seaford and the marina, walking-distance to city centre, cultural and touristic places. Cartagena is famous of its unique artistic heritage, with a number of landmarks such as the Roman Theatre and a lot of Phoenician, Roman, Byzantine and Moorish remains.

The scope of the Conference is concentrated on the applications of transparent and all-optical technologies in telecommunications, computing and novel applications, and includes:

Digital all-optical networks
Ultra-fast optical time domain multiplexing
Ultra-dense wavelength-division multiplexing
Optical switching and routing (WAOR)
Next generation networking
Optical memories and data storage
Optical transparency and network scalability
Network reliability and availability (RONEXT)
Wireless and optical networking (GOWN)
Radio-over-fibre transmission
Broadband metro and access networks
Market in telecommunications (MARS)
Photonics band-gap structures (ESPC)
Photonic crystal fibres
Nonlinear and active PBE devices
Nanoscale and ultrafast photonics (NAON)
VCSELs and other novel light sources
Microwave resonators and photonic molecules (MPM)
Novel glasses
New transmission windows
Polarisation mode dispersion
Photon component integration (PICAW)
Sub-wavelength photonic devices (SWP)
Non-conventional optical communications
Network planning and design tools
Communication in transportation systems (CTS)
Other relevant topics

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<td>Synchronization of the time-domain wavelength interleaved networks</td>
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<td>16:50</td>
<td>We D2.1</td>
<td>Modelling the bandwidth behaviour of fibre Bragg gratings excited by low-frequency acoustic waves (invited)</td>
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<td>Modelling the bandwidth behaviour of fibre Bragg gratings excited by low-frequency acoustic waves (invited)</td>
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<td>16:00</td>
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<td>High resolution optical special filtering technology. Reaching the sub-DHz resolution range (invited)</td>
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<td>16:20</td>
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Thursday, June 27

SESSION Th.11
Chair: Jaromila Millerová (8:30 Thursday, June 27)

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<td>The time lens concept applied to ultra-high-speed OTDM signal processing (invited)</td>
<td>A.T. Clausen, E. Pajuste, M. Hansen, M. Muñoz, M. Hu, J. Lagardera, A. Ghi, L. Kjær, R. Pajuste, J. Pajuste</td>
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<td>9:00 TH1.2</td>
<td>Effect of optical phase regeneration on fiber transmission capacity (invited)</td>
<td>G. Herman, P. Horák</td>
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<td>9:00 TH2.1</td>
<td>Dynamicities of SHB and SFB on 9X9 EDFA: Dependence on spectral allocation of input channels</td>
<td>J.M. Ferreira, D. Fonseca, P. Montero, A.P. Porto, L. Rapp</td>
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<td>9:15 TH2.3</td>
<td>A column generation approach for large-scale RBA-based network planning (invited)</td>
<td>M. Ruiz, M. Żotzikowski, L. Vélez, J. Cornelles</td>
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<td>9:00 TH3.3</td>
<td>A column generation approach for large-scale RBA-based network planning (invited)</td>
<td>M. Ruiz, M. Żotzikowski, L. Vélez, J. Cornelles</td>
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<td>10:00 TH3.5</td>
<td>Giant circular dichroism in chiral materials</td>
<td>P. Römer, M. Karasov, E. Wetzelau, E. Krüger, E. Endt, C. Sabah</td>
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SESSION Th.12
Chair: Jaromila Millerová (8:30 Thursday, June 27)

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<td>10:00</td>
<td>Th.3.4</td>
<td>An adaptive path restoration algorithm based on power series routing for all-optical networks (invited)</td>
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SESSION Th.13
Chair: Marian Marciniski (8:30 Thursday, June 27)

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<td>10:00</td>
<td>Th.3.7</td>
<td>Giant circular dichroism in chiral materials</td>
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**Tu D1.3 Spectral efficiency considerations in mixed-mode WDM-NOMA networks with signal quality guarantee (invited)**
O. Ududea, P. Monti, V. Rodinov, R. Schatz, L. Venckien, G. Aviavos

**Tu D2.3 Membrane infiltration of sarafrol absorbers on silicon as building blocks for transparent optical networks (invited)**
Q. R. Zhao, R. Flourent, H.-J. D. Doren, M. Tassew

**Tu D3.2 Results from the ERC project ACCORDANCE on converged OFDMA-PON networks (invited)**

**Tu D4.3 Storage, scheduling and switching – A new data delivery paradigm in the big data era (invited)**
Wenqiang Sun, Fangzhou Li, Wei Guo, Yachai Jin, Weichen Su

**Tu D5.3 Inverse scattering problems in subsurface diagnostics of hysteresis media (invited)**
P.K. Gnechovich

**Tu D5.2 Reduced polymer fibers (invited)**

**17:00 Tu D1.4 Energy efficiency analysis of next-generation passive optical network (NG-PON) technologies in a major city network (invited)**
S. Lambert, J. Moretto, J.A. Torrijas, B. Lannooy, O. Colle, M. Pickett

**17:00 Tu D5.1 Adaptive bit loading in FHT-based GPON transponders for few-grid optical networks L. Radal, M. Svardol Moraio, J.M. Fabbega, G. Jungferl**

**17:00 Tu D2.3 Highly efficient waveguide lasers at 2 um (invited)**
K. van Dalen, S. Aravazhi, C. Grivak, S.M. Garcia-Bianco, M. Polianau

**17:00 Tu D6.4 Adaptive coding-modulation for the next-generation intelligent optical transport networks (invited)**
J. von Hoyninghausen, W. Rosenkranz

**17:00 Tu D3.2 GPON redundancy eraser algorithm for long-reach extension (invited)**
J. Segarra, V. Saleas, J. Prat

**17:00 Tu D5.4 Traffic demand estimation for hybrid switching systems (invited)**
Weiping Li, Weiping Sun, Steven Xiao, Weichen Su

**17:00 Tu D5.5 Plasmonic materials and metamaterials by bottom-up approach (invited)**
D.A. Pavlov, M. Gao, O. Chumak, K. Sandoval, A. Shcheptik, A. Kiss, A. Berdik, G. Leelih, C. Sibilia

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**Wednesday, June 28**

**SESSION Va1.1 ICTON VIII**
Chair: João Padro (9:00 Wednesday, June 28)

**SESSION Va2.1 Access III**
Chair: Peter Morsol (9:00 Wednesday, June 28)

**SESSION Va3.1 Access III**
Chair: Ioannis Tomkos (9:00 Wednesday, June 28)

**SESSION Va4.1 QC1**
Chair: Lena Woonsenis (9:00 Wednesday, June 28)

**SESSION Va5.1 ESPP I**
Chair: Célia Cogilacaro (9:00 Wednesday, June 28)

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20/20 Gala Dinner at Restaurant “La Cartuja”
ICTON 2013 Preliminary Technical Programme

Tremblay (13:50 Tuesday, June 26)
13:50 TuC1 An ultra-low power solution for elastic optical networks (Invited)
F. Leclerc, C. Belostotski, L. Di Pietro, M. Zorzi
13:50 TuC2 Optical buffering for dynamic and elastic optical networks (Invited)
V. Zorzi, C. Kostoulas, P. Strong, J. Yan, L. Di Pietro

Polb (13:50 Tuesday, June 26)
13:50 CuA.1 Ultra-long reach WPANs (Invited)
A. Manzoni, M. Zorzi
13:50 CuA.2 Optical buffering for dynamic and elastic optical networks (Invited)
V. Zorzi, C. Kostoulas, P. Strong, J. Yan, L. Di Pietro

Parce (13:50 Tuesday, June 26)
13:50 TuC4.1 On the cost of flexible optical networks (Invited)
C. Boccia, A. Manzoni, L. Di Pietro, M. Zorzi
13:50 TuC4.2 On the cost of flexible optical networks (Invited)
C. Boccia, A. Manzoni, L. Di Pietro, M. Zorzi

Vigny (13:50 Tuesday, June 26)
13:50 CuA.4 Fast and ef?cient optical buffering for dynamic and elastic optical networks (Invited)
V. Zorzi, C. Kostoulas, P. Strong, J. Yan, L. Di Pietro

14:10 TuC1 An elastic networks model (Invited)
A. Assadi, T. Rylander, A. Di Seme, A. Casini
14:10 TuC2 An elastic networks model (Invited)
A. Assadi, T. Rylander, A. Di Seme, A. Casini
14:10 CuC.1 An elastic networks model (Invited)
A. Assadi, T. Rylander, A. Di Seme, A. Casini
14:10 CuC.2 An elastic networks model (Invited)
A. Assadi, T. Rylander, A. Di Seme, A. Casini

14:30 TuC1 Optimization algorithms for elastic optical networks (Invited)
M. Klimkowski, K. Kviklewicz, R. Godlewski
14:30 TuC2 Optimization algorithms for elastic optical networks (Invited)
M. Klimkowski, K. Kviklewicz, R. Godlewski
14:30 CuC.1 Optimization algorithms for elastic optical networks (Invited)
M. Klimkowski, K. Kviklewicz, R. Godlewski
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14:50 CuC.2 An elastic networks model (Invited)
A. Assadi, T. Rylander, A. Di Seme, A. Casini

16:00 TuD1 Optical components for signal processing in photonic networks (Invited)
G. Cai, V. Pezzuoli
16:00 TuD2 Optical components for signal processing in photonic networks (Invited)
G. Cai, V. Pezzuoli
16:00 TuD3 Optical components for signal processing in photonic networks (Invited)
G. Cai, V. Pezzuoli
16:00 TuD4 Optical components for signal processing in photonic networks (Invited)
G. Cai, V. Pezzuoli

16:30 TuD1 Dynamic management of bursty traffic over multiple channels (Invited)
A. Somani
16:30 TuD2 Dynamic management of bursty traffic over multiple channels (Invited)
A. Somani
16:30 TuD3 Dynamic management of bursty traffic over multiple channels (Invited)
A. Somani
16:30 TuD4 Dynamic management of bursty traffic over multiple channels (Invited)
A. Somani

16:40 TuE.1 Internet Protocol over Optical Networks (Invited)
R. Vanchiere, G. Bianchi, L. Boccia, A. Manzoni
16:40 TuE.2 Internet Protocol over Optical Networks (Invited)
R. Vanchiere, G. Bianchi, L. Boccia, A. Manzoni
16:40 TuE.3 Internet Protocol over Optical Networks (Invited)
R. Vanchiere, G. Bianchi, L. Boccia, A. Manzoni
16:40 TuE.4 Internet Protocol over Optical Networks (Invited)
R. Vanchiere, G. Bianchi, L. Boccia, A. Manzoni

17:00 TuF.1 Dynamic deployment of virtual OBS switching (Invited)
R. Vanchiere, G. Bianchi, L. Boccia, A. Manzoni
17:00 TuF.2 Dynamic deployment of virtual OBS switching (Invited)
R. Vanchiere, G. Bianchi, L. Boccia, A. Manzoni
17:00 TuF.3 Dynamic deployment of virtual OBS switching (Invited)
R. Vanchiere, G. Bianchi, L. Boccia, A. Manzoni
17:00 TuF.4 Dynamic deployment of virtual OBS switching (Invited)
R. Vanchiere, G. Bianchi, L. Boccia, A. Manzoni

18:00 TuG.1 Dynamic management of bursty traffic over multiple channels (Invited)
A. Somani
18:00 TuG.2 Dynamic management of bursty traffic over multiple channels (Invited)
A. Somani
18:00 TuG.3 Dynamic management of bursty traffic over multiple channels (Invited)
A. Somani
18:00 TuG.4 Dynamic management of bursty traffic over multiple channels (Invited)
A. Somani

18:40 TuH.1 Dynamic management of bursty traffic over multiple channels (Invited)
A. Somani
18:40 TuH.2 Dynamic management of bursty traffic over multiple channels (Invited)
A. Somani
18:40 TuH.3 Dynamic management of bursty traffic over multiple channels (Invited)
A. Somani
18:40 TuH.4 Dynamic management of bursty traffic over multiple channels (Invited)
A. Somani

19:00 TuI.1 Dynamic management of bursty traffic over multiple channels (Invited)
A. Somani
19:00 TuI.2 Dynamic management of bursty traffic over multiple channels (Invited)
A. Somani
19:00 TuI.3 Dynamic management of bursty traffic over multiple channels (Invited)
A. Somani
19:00 TuI.4 Dynamic management of bursty traffic over multiple channels (Invited)
A. Somani

19:20 TuJ.1 Dynamic management of bursty traffic over multiple channels (Invited)
A. Somani
19:20 TuJ.2 Dynamic management of bursty traffic over multiple channels (Invited)
A. Somani
19:20 TuJ.3 Dynamic management of bursty traffic over multiple channels (Invited)
A. Somani
19:20 TuJ.4 Dynamic management of bursty traffic over multiple channels (Invited)
A. Somani

19:40 TuK.1 Dynamic management of bursty traffic over multiple channels (Invited)
A. Somani
19:40 TuK.2 Dynamic management of bursty traffic over multiple channels (Invited)
A. Somani
19:40 TuK.3 Dynamic management of bursty traffic over multiple channels (Invited)
A. Somani
19:40 TuK.4 Dynamic management of bursty traffic over multiple channels (Invited)
A. Somani

18/07/2013