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 $V_{\pi}L$ 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 traveling 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_B, the energy consumption per bit can thus be approximated by $W_{\text{bit}} = (2U_0/2)^2 / R / B_B$. 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.

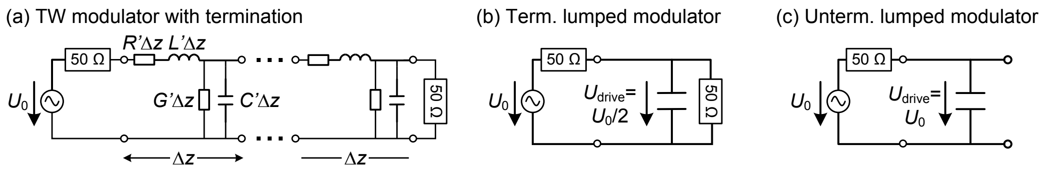

Figure 1. Equivalent circuit models of various modulator types. (a) Traveling-wave modulator. (b) Simplified model of a terminated lumped modulator. The drive voltage $U_0/2$ across the modulator input terminals is half the open-circuit source voltage U_0. The total RF power is dissipated by capacitive loading and by the 50 Ω 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 $V_\pi L$ product of 3.0 Vmm [27]. The modulator can be operated in two ways:

- First, we operate the device with a 50 Ω termination and use a peak-to-peak drive voltage U_{drive} of 800 mV_{pp} (i.e., an amplitude of 400 mV_{p}). The voltage V_π which is needed to switch a MZI modulator from minimum to maximum transmission was found to be 2.5 V_{pp} 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 mV_{pp}.
- 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 $C_{\text{MZM}} = 2\,C_{\text{PM}} = 378\,\text{fF}$, 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).

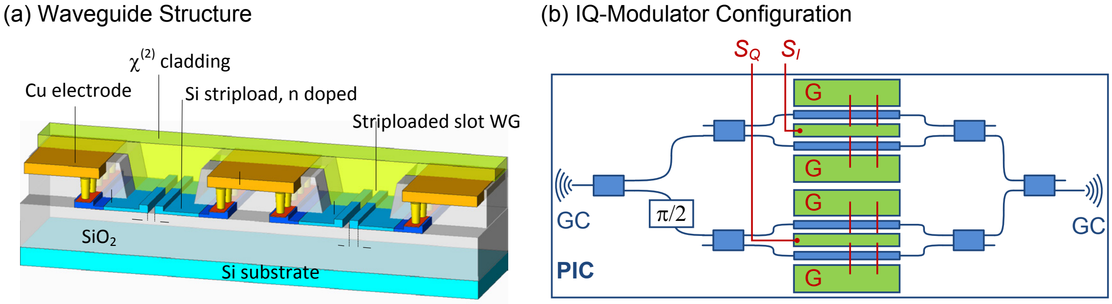

Figure 2: (a) Strip-loaded slot waveguide where metal electrodes are connected to the two rails of the slot waveguide by doped silicon strips (stripload). Both, the modulating field and the optical mode are well confined to the slot. For efficient electro-optic modulation the slot needs to be filled with an adequate electro-optic material. (b) IQ-modulator configuration. More details on the Figures can be found in Ref. [28].

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 $V_{\pi}L$ 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.

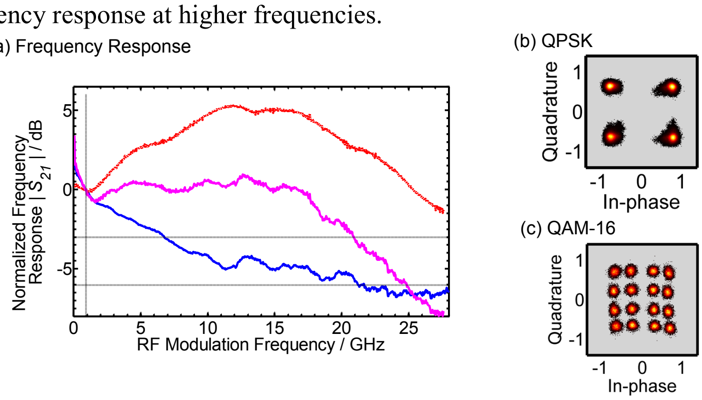

Figure 3: (a) Electro-optic frequency response S_{21} of our MZM. (Magenta line: frequency response of modulator+receiver; blue line: frequency response of modulator; red curve: frequency response of receiver). (b) SOH IQ modulator constellation diagrams for 28 GBd single polarization QPSK at 56 Gbit/s and (c) a 28 GBd single polarization 16-QAM signal with a total of 112 Gbit/s [28].

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 1.2×10^{-3}.

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 Gbit/s up to 640 fJ/bit at 112 Gbit/s [27, 28].

Acknoweldgements

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 Teratronics (HIRST), the Karlsruhe School of Optics and Photonics (KSOP), and the Karlsruhe Nano-Micro Facility (KNMF).

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IEEE Catalog Number: CFP13485-USB
ISBN: 978-1-4799-0682-6

Formal publisher:
National Institute of Telecommunications
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1 Szachowa Street, Warsaw, Poland.

Editors: **Marek Jaworski**, **Marian Marciniak**

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14:30 We.C1.2 Impact of reduced complexity inverse Volterra series transfer function-based nonlinear equalizer in coherent OFDM systems for next-generation core networks(***Invited***) **E. Giacoumidis**, N. J. Doran, I. Aldaya, V. Vgenopoulou, Y. Jaouën	14:20 We.C2.2 Evolution of fabless generic photonic integration (***Invited***) **P. Munoz**, J.D. Domenech, I. Artundo, J.H. den Bested, J. Capmany	14:20 We.C3.2 Self-seeding of semiconductor lasers for next-generation WDM passive optical networks (***Invited***) **M. Presi**, A. Chiuchiarelli, R. Corsini, E. Ciaramella	14:20 We.C4.2 Alternate architectures for an all-optical core network based on new subwavelength switching paradigms (***Invited***) **R. Aparicio-Pardo**, A. Triki, E. Le Rouzic, B. Arzur, E. Pincemin, F. Guillemin	14:20 We.C5.2 Grating resonances as an alternative to plasmon resonances in nanophotonics applications (***Invited***) **A.I. Nosich**, V.O. Byelobrov, O.V. Shapoval, D.M. Natarov, T.L. Zinenko, M. Marciniak	14:20 We.C6.2 Direct inscription of photonic band-gap waveguides into bulk optical glass (***Invited***) **A. Fuerbach**, S. Gross, A. Arriola, M. Alberich, M. Withford
14:50 We.C1.3 Equalization techniques for high-speed OFDM-based access systems using direct modulation and direct detection (***Invited***) N. Sequeira André, K. Habel, **H. Louchet**, A. Richter	14:40 We.C2.3 Nanoscale Si-based photonics for next generation integrated circuits (***Invited***) **L. Wosinski**, Fei Lou, L. Thylén	14:40 We.C3.3 Wavelength protection within coexistence of current and next-generation PON networks (***Invited***) D. Korček, **J. Müllerová**	14:40 We.C4.3 Javanco: A software framework for optical network modelling and optimization (***Invited***) **S. Rumley**, R. Hendry, K. Bergman	14:40 We.C5.3 Excitation and propagation of electromagnetic pulses along dielectric-air interface (***Invited***) **A. Popov**, I. Prokopovich, S. Zapunidi	14:40 We.C6.3 Light scattering from one-dimensional photonic crystals under total internal reflection (***Invited***) **G.V. Morozov**, F. Placido, D.W.L. Sprung
15:10 We.C1.4 Bandwidth variable transponders based on OFDM technology for elastic optical networks (***Invited***) **M. Svaluto Moreolo**, J.M. Fabrega, L. Nadal, F.J. Vilchez, G. Junyent	15:00 We.C2.4 Photonic wire bonding: Nanophotonic interconnects fabricated by direct-write 3D lithography (***Invited***) **C. Koos**, J. Leuthold, W. Freude, N. Lindenmann, S. Koeber, J. Hoffmann, T. Hoose, P. Huebner		15:00 We.C4.4 Cloud orchestration with SDN / OpenFlow in carrier transport networks (***Invited***) **A. Autenrieth**, J-P. Elbers, P. Kaczmarek, P. Kostecki	15:00 We.C5.4 *Ab initio* determination of basic dielectric properties (***Invited***) **A. Quandt**, R. Warmbier	15:00 We.C6.4 Hyperspectral near-field imaging of light bending in a graded photonic crystal (***Invited***) B. Cluzel, J. Dellinger, K-V. Do, E. Cassan, **F. de Fornel**
15:30 We.C1.5 Orthogonal multipulse modulation in optical datacommunications (***Invited***) **J.D. Ingham**, R.V. Penty, I.H. White				15:20 We.C5.5 Design and simulation of apodized SOI fiber to chip coupler by sub-wavelength structure (***Invited***) J. Chovan, A. Kuzma, **F. Uherek**	15:20 We.C6.5 Negative diffraction by a periodically modulated loss (***Invited***) **M. Botey**, N. Kumar, R. Herrero, L. Maigyte, R. Pico, K. Staliunas 15:40 We.C6.6 Optical absorption enhancement by quasi-photonic crystals in thin films for photovoltaic applications (***Invited***) **P.A. Postigo**, J. M. Llorens
Coffee break (15:50 – 16:10)	***Coffee break*** (15:20 – 15:50)	***Coffee break*** (15:00 – 15:30)	***Coffee break*** (15:20 – 15:40)	***Coffee break*** (15:40 – 16:10)	***Coffee break*** (16:00 – 16:20)
SESSION We.D1 **ICTON XI** *Chair:* ***Ivan Djordjevic*** **(16:10 Wednesday, June 26)**	**SESSION We.D2** **ICTON XV** *Chair:* ***Maciej Dems*** **(15:50 Wednesday, June 26)**	**SESSION We.D3** **ASTRON/FOX-C** *Chair:* ***Gabriella Cincotti*** **(15:30 Wednesday, June 26)**	**SESSION We.D4** **RONEXT** *Chair:* ***Paolo Monti*** **(15:40 Wednesday, June 26)**	**SESSION We.D5** **SWP XI** *Chair:* ***Robert Czaplicki*** **(16:10 Wednesday, June 26)**	**SESSION We.D6** **NAVOLCHI/SOFI** *Chair:* ***Ioannis Tomkos*** **(16:20 Wednesday, June 26)**
16:10 We.D1.1 Next generation optical network and its optical components (***Invited***) **Yaping Zhang**	15:50 We.D2.1 High-speed, low-power optical modulators in silicon (***Invited***) **J. Leuthold**, C. Koos, W. Freude, L. Alloatti, R. Palmer, D. Korn, J. Pfeifle, M. Lauermann, R. Dinu, S. Wehrli, M. Jazbinsek, P. Gunter, M. Waldow, T. Wahlbrink, J. Bolten, M. Fournier, J.M. Fedeli, W. Bogaerts, H. Yu	15:30 We.D3.1 All-optical implementation of OFDM/NWDM Tx/Rx (***Invited***) J. Hoxha, **G. Cincotti**, N.P. Diamantopoulos, P. Zakynthinos, I. Tomkos	15:40 We.D4.1 Core network physical topology design for energy efficiency and resilience (***Invited***) T.E.H. El-Gorashi, Xiaowen Dong, A. Lawey, **J.M.H. Elmirghani**	16:10 We.D5.1 Metamaterial fishnet structures and small (70 nm) split ring resonators formed by nanoimprint lithography (***Invited***) **N.P. Johnson**, G.J. Sharp, M. Yuce, Xiaolon Hu, M. Sinworapun, A.Z. Khokhar	16:20 We.D6.1 Waveguide-coupled nanolasers in III-V membranes on silicon (***Invited***) **V. Dolores-Calzadilla**, D. Heiss, A. Fiore, M. Smit
16:20 We.D1.2 Dual stage carrier phase estimation for 16-QAM systems based on a modified QPSK-partitioning algorithm **S.M. Bilal**, G. Bosco	16:10 We.D2.2 High performance travelling wave Mach-Zehnder modulators for emerging generations of high capacity transmitter	15:50 We.D3.2 Nyquist-WDM-based system performance evaluation (***Invited***) **R.I. Killey**, M. Sezer Erkilinc, R. Maher, M. Paskov,	16:00 We.D4.2 Multicast service for UltraFlow access networks (***Invited***) **D. Larrabeiti**, L. Kazovsky, M.I. Urueña,	16:30 We.D5.2 Plasmonic dimer metamaterials and metasurfaces for polarization control of terahertz and optical waves (***Invited***) S.V. Zhukovsky,	16:40 We.D6.2 Optical properties of SOI waveguides functionalized with close-packed quantum dot films (***Invited***)

15th International Conference on Transparent Optical Networks

	components (***Invited***) ***R. Kaiser***, *B. Gomez Saavedra, K.O. Velthaus, M. Gruner, M. Hamacher, D. Hoffmann, M. Schell*	*S. Kilmurray, R. Bouziane, B.C. Thomsen, S.J. Savory, P. Bayvel*	*A.R. Dhaini, Shuang Yin, J.A. Hernández, P. Reviriego, T. Shunrong Shen*	*M. Zalkovskij, R. Malureanu, A. Andryieuski, A. Novitsky, P.U. Jepsen,* ***A.V. Lavrinenko***, *P. T. Tang, C. Kremers, D.N. Chigrin*	***Z. Hens***, *A. Omari, P. Geiregat, D. Van Thourhout*
16:35 **We.D1.3** Synchronization of the time-domain wavelength interleaved networks ***I. Popescu***, *L. Sadeghioon, A. Gravey, P. Gravey, M. Morvan*	16:30 **We.D2.3** Application of extended Taylor series based finite difference method in photonics (***Invited***) ***S. Sujecki***	16:10 **We.D3.3** High resolution optical spectral filtering technology: Reaching the sub-GHz resolution range (***Invited***) ***D.M. Marom***, *D. Sinefeld, O. Golani, N. Goldshtein, R. Zektzer, R. Rudnick*	16:20 **We.D4.3** Optimal technicians' allocation problem with respect to failure reparation (***Invited***) ***C. Mas Machuca***, *B. de la Cruz Miranda*	16:50 **We.D5.3** Low-loss and multi-band metamaterials (***Invited***) ***C. Sabah***	17:00 **We.D6.3** Light coupling from active polymer layers to hybrid dielectric-plasmonic waveguides (***Invited***) ***I. Suárez***, *E.P. Fitrakis, H. Gordillo, P. Rodríguez-Cantó, R. Abargues, I. Tomkos, J. Martínez-Pastor*
16:50 **We.D1.4** Performance enhancement of partial-42.7Gb/s DPSK via an asymmetrical receiver design ***N.J. Murray***, *O.A. Olubodun, P. Harper, N.J. Doran*	16:50 **We.D2.4** Modelling the bandwidth behaviour of fibre Bragg gratings excited by low-frequency acoustic waves (***Invited***) ***A. de Almeida Prado Pohl***, *R.E. da Silva, M.A. Ruggieri Franco, P. de Tarso Neves Jr., H. Bartelt*	16:30 **We.D3.4** Almost-optimal design for optical networks with Hadoop cloud computing: Ten ordinary desktops solve 500-node, 1000-link, and 4000-request RWA problem within three hours (***Invited***) ***Gangxiang Shen***, *Yongcheng Li, Limei Peng*	16:40 **We.D4.4** Balancing the benefits inherent in reconfigurable coherent optical transceivers (***Invited***) ***B.T. Teipen***, *M.H. Eiselt*	17:10 **We.D5.4** Energy flow canalization of evanescent cylindrical-vector beams (***Invited***) ***C.J. Zapata-Rodríguez***, *J.J. Miret*	17:20 **We.D6.4** Low energy routing platforms for optical interconnects using active plasmonics integrated with silicon photonics (***Invited***) ***K. Vyrsokinos***, *S. Papaioannou, D. Kalavrouziotis, F. Zacharatos, L. Markey, J-C. Weeber, A. Dereux, A. Kumar, S.I. Bozhevolnyi, M. Waldow, G. Giannoulis, D. Apostolopoulos, T. Tekin, H. Avramopoulos, N. Pleros*
17:05 **We.D1.5** Performance evaluation of strongly filtered asymmetric 42.7 Gb/s coherent 50% RZ-BPSK system ***O.A. Olubodun***, *N.J. Murray, P. Harper, N.J. Doran*		16:50 **We.D3.5** Towards 400G/1T flexible optical transport networks (***Invited***) ***E. Pincemin***, *M. Song, Y. Loussouarn, G. Thouenon, C. Betoule*	17:00 **We.D4.5** Energy saving in access networks: Gain or loss from the cost perspective? (***Invited***) *P. Wiatr, J. Chen, P. Monti,* ***L. Wosinska***		
			17:20 **We.D4.6** Dynamic traffic provisioning in mixed-line-rate networks with launch power determination (***Invited***) *H. Cukurtepe,* ***A. Yayimli***, *M. Tornatore, B. Mukherjee*		

Thursday, June 27

SESSION Th.A1	SESSION Th.A2	SESSION Th.A3	SESSION Th.A4	SESSION Th.A5	SESSION Th.A6
ICTON XII Chair: ***Jarmila Müllerová*** **(8:30 Thursday, June 27)**	**ICTON XVI** Chair: ***Elzbieta Bereś-Pawlik*** **(8:30 Thursday, June 27)**	**NeO III** Chair: ***Walter Cerroni*** **(8:30 Thursday, June 27)**	**WAOR II** Chair: ***Pablo Pavón Mariño*** **(8:30 Thursday, June 27)**	**SWP XII** Chair: ***Sergei Zhukovsky*** **(8:30 Thursday, June 27)**	**NSON** Chair: ***Marian Marciniak*** **(8:30 Thursday, June 27)**
8:30 **Th.A1.1** The time lens concept applied to ultra-high-speed OTDM signal processing (***Invited***) ***A.T. Clausen***, *E. Palushani, H.C. Hansen Mulvad, H. Hu, J. Laguardia Areal, M. Galili, L.K. Oxenløwe, P. Jeppesen*	8:30 **Th.A2.1** WDM-enabled optical RAM architectures for ultra-fast, low-power optical cache memories (***Invited***) *G.T. Kanellos, T. Alexoudi, D. Fitsios, C. Vagionas, P. Maniotis, S. Papaioannou, A. Miliou,* ***N. Pleros***	8:30 **Th.A3.1** Anycast end-to-end resilience for cloud services over virtual optical networks (***Invited***) *Minh Bui, B. Jaumard,* ***C. Develder***	8:30 **Th.A4.1** Performance of ring-resonator based optical backplane in high capacity routers (***Invited***) *G. Rizzelli, D. Siracusa,* ***G. Maier***, *M. Magarini, A. Melloni*	8:30 **Th.A5.1** Radial Bragg laser as a miniaturized rotation sensor (***Invited***) *E. Ben-Basat, Y. Karni,* ***J. Scheuer***	8:30 **Th.A6.1** Inverse design of novel nanophotonic structures (***Invited***) ***I. Andonegui***, *A. Blanco, I. Calvo, A.J. Garcia-Adeva*
8:50 **Th.A1.2** Effect of all-optical phase regeneration on fiber transmission capacity (***Invited***) *G. Hesketh,* ***P. Horak***	8:50 **Th.A2.2** Optimizing silicon-on-oxide 2D-grating couplers ***L. Carroll***, *D. Gerace, I. Cristiani, L.C. Andreani*	8:50 **Th.A3.2** Routing and network design for HEAnet (***Invited***) ***D. Mehta***, *B. O'Sullivan, L. Quesada, M. Ruffini, D. Payne, L. Doyle*	8:50 **Th.A4.2** Scalable and energy-efficient optical tree-based greedy router (***Invited***) *S. Sahhaf, A. Dixit, W. Tavernier,* ***D. Colle***, *M. Pickavet, P. Demeester*	8:50 **Th.A5.2** Simulation of optical Bloch oscillations and breathing modes in the waveguide arrays ***M. Gozman***, *Y. Polishchuk, I. Polishchuk*	8:50 **Th.A6.2** Nonlinear complex photonic structures (***Invited***) ***M. Boguslawski***, *P. Rose, F. Diebel, S. Brake, C. Denz*
9:10 **Th.A1.3** Digitally processed modulation formats and integrated photonics for flexible optical metro-access networks (***Invited***) ***J.A. Lázaro***, *B. Schrenk, M. Malligaraj, I. Cano, M. Sridharan, G. Junyent*	9:05 **Th.A2.3** Dynamics of SHB and SDP on 9XX EDFAs: Dependence on spectral allocation of input channels ***J.M. Ferreira***, *D. Fonseca, P. Monteiro, A.N. Pinto, L. Rapp*	9:10 **Th.A3.3** A column generation approach for large-scale RSA-based network planning (***Invited***) ***M. Ruiz***, *M. Żotkiewicz, L. Velasco, J. Comellas*	9:10 **Th.A4.3** An adaptive path restoration algorithm based on power series routing for all-optical networks (***Invited***) *C.J.A. Bastos-Filho, R.C. Freitas,* ***D.A.R. Chaves***, *R.C.L. Silva, M.L.P. Freire, H.A. Pereira, J.F. Martins-Filho*	9:05 **Th.A5.3** Giant circular dichroism in chiral metamaterials ***F. Dincer***, *M. Karaaslan, E. Unal, M. Bakir, U. Erdiven, C. Sabah*	9:10 **Th.A6.3** Ways to optimize the second-harmonic response from metamaterials (***Invited***) ***R. Czaplicki***, *H. Husu, M. Zdanowicz, J. Mäkitalo, K. Koskinen, R. Siikanen, J. Laukkanen, J. Lehtolahti,*

Tu.D1.3 Spectral and energy efficiency considerations in mixed-line rate WDM networks with signal quality guarantee (*Invited*) A. Udalcovs, **P. Monti**, V. Bobrovs, R. Schatz, L. Wosinska, G. Ivanovs	Tu.D2.3 Membrane InP saturable absorbers on silicon as building blocks for transparent optical networks (*Invited*) **O. Raz**, G. Roelkens, H.J.S. Dorren, M. Tassaert	Tu.D3.3 Results from the EU project ACCORDANCE on converged OFDMA-PON networks (*Invited*) **K. Kanonakis**, I. Tomkos, H.-G. Krimmel, F. Schaich, C. Lange, E. Weis, M. Dreschmann, R. Schmogrow, P. Kourtessis, M. Milosavljevic, I. Cano, J. Prat, J.A. Torrijos Gijón	Tu.D4.3 Storage, schedule and switching – A new data delivery paradigm in the big data era? (*Invited*) **Weiqiang Sun**, Fengqin Li, Wei Guo, Yaohui Jin, Weisheng Hu	Tu.D5.3 Inverse scattering problems in subsurface diagnostics of inhomogeneous media (*Invited*) **K.P. Gaikovich**	Tu.D6.3 Eu-doped polymer fibers (*Invited*) **R. Caspary**, S. Möhl, A. Cichosch, R. Evert, S. Schütz, H-H. Johannes, W. Kowalsky
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. Montalvo, J.A. Torrijos, **B. Lannoo**, D. Colle, M. Pickavet	17:00 Tu.D2.4 Highly efficient channel waveguide lasers at 2 µm (*Invited*) K. van Dalfsen, S. Aravazhi, C. Grivas, S.M. García-Blanco, **M. Pollnau**	16:40 Tu.D3.4 Passive optical networks based on OFDM: Perspectives and experimental verifications (*Invited*) **J. von Hoyningen-Huene**, W. Rosenkranz	17:00 Tu.D4.4 Adaptive coded-modulation for the next-generation intelligent optical transport networks **Yequn Zhang**, I.B. Djordjevic	17:00 Tu.D5.4 Why optical nonlinear characterisation using imaging technique is a better choice? (*Invited*) **G. Boudebs**, V. Besse, C. Cassagne, H. Leblond, F. Sanchez	
17:20 Tu.D1.5 Adaptive bit loading in FHT-based OFDM transponders for flexi-grid optical networks **L. Nadal**, M. Svaluto Moreolo, J.M. Fàbrega, G. Junyent	17:20 Tu.D2.5 Microring resonators: Opportunities and challenges for future optical networks (*Invited*) **A. Bianco**, M. Garrich, R. Gaudino, Jinan Xia	17:00 Tu.D3.5 GPON redundancy eraser algorithm for long-reach extension (*Invited*) **J. Segarra**, V. Sales, J. Prat	17:20 Tu.D4.5 Traffic demand estimation for hybrid switching systems **Pingqing Li**, Weiqiang Sun, Shilin Xiao, Weisheng Hu	17:20 Tu.D5.5 Plasmonic materials and metamaterials by bottom-up approach: Manufacturing and properties (*Invited*) **D.A. Pawlak**, M. Gajc, P. Osewski, K. Sadecka, A. Stefanski, A. Klos, A. Belardini, G. Leahu, C. Sibilia	

20:00 ***Gala Dinner at Restaurant "La Cartuja"***

Wednesday, June 26

SESSION We.A1 ICTON VIII Chair: **João Pedro** (9:00 Wednesday, June 26)	SESSION We.A2 PICAW II Chair: **Peter Horak** (9:00 Wednesday, June 26)	SESSION We.A3 Access III Chair: **Ioannis Tomkos** (9:00 Wednesday, June 26)	SESSION We.A4 GOC I Chair: **Lena Wosinska** (9:00 Wednesday, June 26)	SESSION We.A5 SWP VIII Chair: **Brana Jelenković** (9:00 Wednesday, June 26)	SESSION We.A6 ESPC I Chair: **Crina Cojocaru** (9:00 Wednesday, June 26)
9:00 We.A1.1 Creating new generation optical network service (*Invited*) **N. Yamanaka**, H. Takeshita, S. Okamoto, T. Sato	9:00 We.A2.1 Optical delay in silicon photonic crystals using ultrafast indirect photonic transitions (*Invited*) **D.M. Beggs**, I.H. Rey, T. Kampfrath, N. Rotenberg, L. Kuipers, T.F. Krauss	9:00 We.A3.1 Optical single sideband generation optimized to support multi-services OFDM over hybrid long-reach FTTH networks **P. Almeida**, H. Silva	9:00 We.A4.1 Energy-efficient space-time optical interconnection architectures for data centers (*Invited*) **P. Castoldi**, I. Cerutti, P.G. Raponi, N. Andriolli, O. Liboiron-Ladouceur	9:00 We.A5.1 Self-pulsing and nonlinear dynamics in micro and nanolasers (*Invited*) **S. Barbay**, F. Selmi, S. Haddadi, R. Braive, I. Sagnes, R. Kuszelewicz, A.M. Yacomotti	9:00 We.A6.1 Asymmetric light propagation in photonic devices (*Invited*) **H. Kurt**
9:20 We.A1.2 Dynamic grooming and spectrum allocation in optical metro ring networks with flexible grid (*Invited*) F. Musumeci, F. Puleio, **M. Tornatore**	9:20 We.A2.2 Numerical simulation and design of organic integrated optical circuits: The PHOTOPOLIS approach (*Invited*) **T. Kamalakis**, D. Alexandropoulos, G. Dede, P. Kanakis, T. Politi, N. Vainos	9:20 We.A3.2 OFDM-PON performance with limited quantization **X. Escayola**, I. Cano, M. Santos, J. Prat	9:20 We.A4.2 Enhancing data centre networking using energy aware optical interconnects (*Invited*) **I. Glesk**, T. Osadola, S. Idris	9:20 We.A5.2 Effect of shell size on single photon emission performances of core/shell dot-in-rods colloidal nanocrystals (*Invited*) F. Pisanello, G. Leménager, L. Martiradonna, L. Carbone, A. Bramati, **M. De Vittorio**	9:20 We.A6.2 Controlling the emission from single quantum dots with electro-opto-mechanical photonic crystal cavities (*Invited*) **L. Midolo**, F. Pagliano, T. B. Hoang, T. Xia, F.W.M. van Otten, A. Fiore, L.H. Li, E.H. Linfield, M. Lermer, S. Höfling
9:40 We.A1.3 Flexible next-generation optical access (*Invited*) **M. Forzati**, A. Gavler	9:40 We.A2.3 A polymer waveguide-based 40 Gb/s optical bus backplane for board-level optical interconnects (*Invited*) **N. Bamiedakis**, A. Hashim, R.V. Penty, I.H. White	9:35 We.A3.3 16×2.5 Gbit/s and 5 Gbit/s WDM PON based on self-seeded RSOA **Sy Dat Le**, Q. Deniel, F. Saliou, A. Lebreton, P. Chanclou	9:40 We.A4.3 Energy-efficient, high-performance optoelectronic packet switching for intra-data center network (*Invited*) **Ken-ichi Kitayama**, S. Debnath, Y. Yoshida, R. Takahashi, A. Hiramatsu	9:40 We.A5.3 Super spontaneous four-wave mixing (*Invited*) **M. Liscidini**, T. Onodera, L.G. Helt, J.E. Sipe	9:40 We.A6.3 Active photonic crystal switches: Modeling, design and experimental characterization (*Invited*) **M. Heuck**, Y. Yu, P.T. Kristensen, N. Kuznetsova, K. Yvind, J. Mørk
10:00 We.A1.4 Dispersion constraints in optical burst switched metropolitan networks with WDM/OCDM technology **L.H. Bonani**, A.B. dos Santos, L. Galdino	10:00 We.A2.4 Robust multi-objective optimization of 2x2 multimode interference coupler using expected improvement **S. ur Rehman**, M. Langelaar, F. van Keulen	9:50 We.A3.4 Optimal trade-off for a bidirectional single-fibre single-wavelength TDM-PON rSOA-based ONU **E.T. López**, V. Polo, J.A. Lázaro, J. Prat	10:00 We.A4.4 Energy saving in TWDM(A) PONs: Challenges and opportunities (*Invited*) **L. Valcarenghi**, P. Castoldi, Y. Yoshida, A. Maruta, Ken-ichi Kitayama	10:00 We.A5.4 Surface enhanced Raman scattering and photo-luminescence through Bloch surface waves in dielectric multilayers (*Invited*) S. Pirotta, X.G. Xu, A. Delfan, S. Mysore, S. Maiti, G. Dacarro, M. Patrini, G. Guizzetti, D. Bajoni, J.E. Sipe, G.C. Walker, M. Liscidini, **M. Galli**	10:00 We.A6.4 Multiple functionality in III-V on SOI hybrid photonic crystals for systems applications (*Invited*) F. Raineri, P. Monnier, **R. Raj**, A. Bazin
10:15 We.A1.5 An efficient add/drop architecture for large-scale subsystem-modular OXC **H. Ishida**,		10:05 We.A3.5 Off-set filtering for enhanced transmission in RSOA based WDM-PON **A. Gatto**, P. Parolari, L. Marazzi, M. Brunero,	10:20 We.A4.5 A blocking analysis for green WDM networks with transponder power management **F. Musumeci**, M. Tornatore,		

Tremblay (13:50 Tuesday, June 25)	Pohl (13:50 Tuesday, June 25)	(13:30 Tuesday, June 25)	Parca (13:50 Tuesday, June 25)	Chair: **Rafał Kotyński** (13:50 Tuesday, June 25)	**Vigreux** (13:30 Tuesday, June 25)
13:50 Tu.C1.1 Trunk reservation for elastic optical networks (*Invited*) F. Lezama Cruzvillasante, **F. Callegati**, W. Cerroni, L.H. Bonani	13:50 Tu.C2.1 Are few-mode fibres: A practical solution to the capacity crunch? (*Invited*) **A. Ellis**, N. Doran	13:30 Tu.C3.1 UltraFlow Access Networks: A dual-mode solution for the access bottleneck (*Invited*) **L.G. Kazovsky**, A.R. Dhaini, M. De Leenheer, T.S. Shen, Shuang Yin, B.A. Detwiler	13:50 Tu.C4.1 On the cost efficiency of flexible optical networking compared to conventional SLR/MLR WDM networks (*Invited*) I. Stiakogiannakis, E. Palkopoulou, **I. Tomkos**	13:50 Tu.C5.1 3D optical data storage by nonlinear processes in thin films of coumarin-containing copolymers (*Invited*) **D. Gindre**, E. Champigny, K. Iliopoulos, M. Sallé	13:30 Tu.C6.1 Chalcogenide-silica fibers: A new base for linear and nonlinear nanophotonic devices (*Invited*) **M.A. Schmidt**
14:10 Tu.C1.2 An elastic networks OMNET++ -based simulator (*Invited*) A. Asensio, A. Castro, L. Velasco, **J. Comellas**	14:10 Tu.C2.2 Ultra-large capacity transmission over trans-oceanic distances with multi-core fibers and EDFAs (*Invited*) **M. Suzuki**, H. Takahashi, K. Igarashi, K. Takeshima, T. Tsuritani, I. Morita	13:50 Tu.C3.2 Towards ultra-dense wavelength-to-the-user: The approach of the COCONUT project (*Invited*) J. Prat, M. Angelou, C. Kazmierski, R. Pous, M. Presi, A. Rafel, G. Vall-llosera, I. Tomkos, **E. Ciaramella**	14:10 Tu.C4.2 Twenty years of open fibre network in Stockholm: A socio-economic study (*Invited*) **M. Forzati**, C. Mattsson	14:10 Tu.C5.2 Self-assembly of nanostructures by a phase separation in holographic layers of dichromated polysaccharide (*Invited*) S. Savić-Šević, D. Pantelić, B. Jokić, **B. Jelenković**	13:50 Tu.C6.2 Chalcogenide glass fibers for photonic devices (*Invited*) **J.L. Adam**, L. Brilland, P. Toupin, V. Nazabal, J. Troles
14:30 Tu.C1.3 Optimization algorithms for data center location problem in elastic optical networks (*Invited*) **M. Klinkowski**, K. Walkowiak, R. Goścień	14:30 Tu.C2.3 On the dependence of differential mode delay of few-mode fibers with the number of modes (*Invited*) F. Ferreira, **D. Fonseca**, H. Silva	14:10 Tu.C3.3 High-speed coherent WDM PON for next-generation access network (*Invited*) **Y.C. Chung**	14:30 Tu.C4.3 Total cost of ownership comparison between single and mixed line rates networks (*Invited*) **A.N. Pinto**, R.M. Morais, J. Pedro, P. Monteiro	14:30 Tu.C5.3 Fluorescent nanoparticles for biosensing applications (*Invited*) **S. Tomljenovic-Hanic**, B.C. Gibson, T.J. Karle, A. Khalid, K. Chung, D.A. Simpson, P. Tran, P. Domachuk, H. Tao, J.E. Moreau, D.L. Kaplan, F.G. Omenetto, H. Amekura, A.B. Djurisic	14:10 Tu.C6.3 Third-order non-linear optical response in chalcogenide glasses: Measurement and evaluation (*Invited*) **E. Romanova**, K. Chumakov, A. Mouskeftaras, S. Guizard, N. Abdel-Moneim, D. Furniss, A.B. Seddon, T.M. Benson
14:50 Tu.C1.4 Spectrum-sliced elastic optical networking (*Invited*) **H. Waldman**, R.C. Almeida Jr., K.D. Assis, R.C. Bortoletto	14:50 Tu.C2.4 Generating versatile waveforms using single dual-drive modulator (*Invited*) B. Dai, S. Shimizu, **Xu Wang**, N. Wada	14:30 Tu.C3.4 Ultra high capacity PON systems (*Invited*) **A. Teixeira**, G. Parca, A. Shahpari, J. Reis, R. Ferreira, A. Abdalla, M. Lima, V. Carrozzo, G. Tosi-Beleffi	14:50 Tu.C4.4 The cost dependence between the grooming scheme, the node architecture and the traffic pattern in optical networks (*Invited*) **R.M. Morais**, J. Pedro, P. Monteiro, A.N. Pinto	14:50 Tu.C5.4 Investigations at nanoscale by using fluorescence in apertureless scanning near field microscopy (*Invited*) **G.A. Stanciu**, D.E. Tranca, R. Hristu, C. Stoichita, S.G. Stanciu	14:30 Tu.C6.4 Nd^{3+} doped phosphate glass optical fibre lasers (*Invited*) **N.G. Boetti**, J. Lousteau, E. Mura, G.C. Scarpignato, D. Milanese
15:10 Tu.C1.5 Flexible-sense optical transmission (*Invited*) V. Rozental, G. Bruno, A. Soso, M. Camera, **D.A.A. Mello**	15:10 Tu.C2.5 Robustness to mechanical perturbations of centre-launching technique in multi-mode fibres for transparent optical interconnects **A. Boletti**, P. Boffi, A. Gatto, P. Martelli, E. Centeno Nieves, M. Martinelli	14:50 Tu.C3.5 COCONUT requirements for residential, business and outdoor scenarios **G. Vall-llosera**, A. Rafel, E. Ciaramella, J. Prat	15:10 Tu.C4.5 Performance comparison of optical channel formats to realize 400G data rates in transport networks under dynamic traffic (*Invited*) **J. Pedro**, A. Eira, J. Pires	15:10 Tu.C5.5 Detecting cancerous tissues in human body by means of fiber fluorescent spectroscopy (*Invited*) **E. Bereś-Pawlik**, H. Sławska, Ł. Klonowski	14:50 Tu.C6.5 Design of rare-earth doped microspheres lasers (*Invited*) P. Bia, L. Mescia, O. Losito, M. De Sario, D. Ristic, M. Ferrari, G.C. Righini, **F. Prudenzano**
Coffee break (15:30 – 16:00)	**Coffee break** (15:30 – 16:00)	**Coffee break** (15:05 – 15:40)	**Coffee break** (15:30 – 16:00)	**Coffee break** (15:30 – 16:00)	**Coffee break** (15:10 – 15:40)
SESSION Tu.D1 **ICTON VII** Chair: **Burak Kantarci** (16:00 Tuesday, June 25)	**SESSION Tu.D2** **PICAW I** Chair: **Lech Wosinski** (16:00 Tuesday, June 25)	**SESSION Tu.D3** **Access II** Chair: **Leonid Kazovsky** (15:40 Tuesday, June 25)	**SESSION Tu.D4** **ISOND** Chair: **Milorad Cvijetic** (16:00 Tuesday, June 25)	**SESSION Tu.D5** **SWP VII** Chair: **Pavel Cheben** (16:00 Tuesday, June 25)	**SESSION Tu.D6** **Glasses II** Chair: **Sławomir Sujecki** (15:40 Tuesday, June 25)
16:00 Tu.D1.1 Dynamic deployment of virtual GMPLS-controlled elastic optical networks using a virtual network resource broker on the ADRENALINE testbed (*Invited*) **R. Vilalta**, R. Muñoz, R. Casellas, R. Martínez	16:00 Tu.D2.1 Photonic components for signal routing in optical networks on chip (*Invited*) G. Calò, **V. Petruzzelli**	15:40 Tu.D3.1 A study of flexible bandwidth allocation in statistical OFDM-based PON (*Invited*) **I.N. Cano**, X. Escayola, A. Peralta, V. Polo, M.C. Santos, J. Prat	16:00 Tu.D4.1 An evolutionary spectrum assignment algorithm for elastic optical networks (*Invited*) **R.C. Almeida Jr.**, R.A. Delgado, C.J.A. Bastos-Filho, D.A.R. Chaves, H.A. Pereira, J.F. Martins-Filho	16:00 Tu.D5.1 High resolution Fourier-transform microspectroscopy based on spiral silicon waveguides (*Invited*) A.V. Velasco, **M.L. Calvo**, P. Cheben, M. Florjańczyk, P.J. Bock, A. Delâge, J.H. Schmid, J. Lapointe, S. Janz, Dan-Xia Xu, M. Vachon	15:40 Tu.D6.1 Te-Ge-Se thermally co-evaporated films: Elaboration, characterization and use for the manufacture of IR rib waveguides, basic elements of CO_2 microsensors (*Invited*) **C. Vigreux**, M. Vu Thi, G. Maulion, R. Kribich, A. Pradel
16:20 Tu.D1.2 Dynamic management of bursty traffic over multiple channels (*Invited*) **A.K. Somani**	16:20 Tu.D2.2 Silicon CMOS photonics platform for enabling high-speed DQPSK transceivers (*Invited*) **P. Sanchis**, M. Aamer, A. Brimont, A.M. Gutierrez, N. Sotiropoulos, H. de Waardt, D.J. Thomson, F.Y. Gardes, G.T. Reed, K. Ribaud, P. Grosse, J.M. Hartmann, J-M. Fedeli, D. Marris-Morini, E. Cassan, L. Vivien, D. Vermeulen, G. Roelkens, A. Hakansson	16:00 Tu.D3.2 Dynamic bandwidth allocation with optimal wavelength switching in TWDM-PONs (*Invited*) **A. Dixit**, B. Lannoo, D. Colle, M. Pickavet, P. Demeester	16:20 Tu.D4.2 Flow controlled scalable optical packet switch for low latency flat data center network (*Invited*) **N. Calabretta**, S. Di Lucente, Jun Luo, A. Rohit, K. Williams, H. Dorren	16:20 Tu.D5.2 Optical Haar transform for 2D processing and compression (*Invited*) **G. Parca**, P. Teixeira, C. Vicente, A. Teixeira	16:00 Tu.D6.2 Active waveguides for Mid-IR (3–4 μm) wavelengths fabricated by femtosecond laser inscription in Dy^{3+} doped tellurite glass (*Invited*) **T.T. Fernandez**, B.D.O. Richards, G. Jose, A. Jha, J. Hoyo, A. Ruiz De la Cruz, J. Solis
16:40	16:40	16:20	16:40	16:40	16:20