Wavelength selective photonic integrated switches for ROADM node functionality in ultrahigh capacity metro network

Netsanet Tessema, Eindhoven University of Technology, 5612 AZ, The Netherlands, n.tessema@tue.nl

Kristif Prifti, Eindhoven University of Technology, 5612 AZ, The Netherlands, k.prifti@tue.nl

Timo Aalto, VTT Research Center of Finland Ltd, 02150, Espoo, Finland, Timo.Aalto@vtt.fi

Giovanni Delrosso, VTT Research Center of Finland Ltd, 02150, Espoo, Finland, Giovanni.Delrosso@vtt.fi

Aref Rasoulzadehzali, Eindhoven University of Technology, 5612 AZ, The Netherlands, a.rasoulzadehzali@tue.nl

Ripalta Stabile, Eindhoven University of Technology, 5612 AZ, The Netherlands, r.stabile@tue.nl

Srivathsa Bhat, VTT Research Center of Finland Ltd, 02150, Espoo, Finland, Srivathsa.Bhat@vtt.fi

Yu Wang, Eindhoven University of Technology, 5612 AZ, The Netherlands, e-mail: y.wang13@tue.nl

Nicola Calabretta,Eindhoven University of Technology, 5612 AZ, The Netherlands,: n.calabretta@tue.nl

***Abstract*— Photonic integrated wavelength selective switches are integral part of Reconfigurable add/drop multiplexer nodes and enable efficient utilization of resources in high-capacity metro networks. Photonic integrated wavelength selective switches play instrumental role in enabling dynamic re-configurability and support efficient utilization of network resources. In this paper, design, and implementation of modular photonic integrated wavelength selective switches across integration platforms is presented. The modularity feature of the photonic integrated circuits (PIC) supports scalability for meeting the capacity requirement of the network. An experimental demonstration on a proof-of-concept SiPh/InP hybrid integrated wavelength selective switches is given. Results further verify the prospect of modular PIC implementation of WSS in fulfilling the dynamic re-configurability demand of high-capacity metro network.**

Keywords— metro-core, metro-access, switching, hybrid, monolithic, WSS

I. Introduction

Boosted by cloud, IoT and 5G applications, next generation metro networks should be able to handle large heterogeneous data traffics dynamically and efficiently [1]. The metro-core network is constituted by high capacity switching reconfigurable add and drop multiplexer (ROADM) nodes referred in this paper as Level-1 (L1) nodes connected in a ring network as depicted in Fig.1. Multi-core fibres are used for carrying bundled traffic in L1 ring network. The real-time information of the traffic flow is provided by software defined network (SDN) controller. The L1 switching nodes are connected to access network constituted by a network of Level-2 (L2) nodes. The L2 nodes are the closest to the end users and may be connected in a varying topology, a ring topology can be an example, as presented in Fig. 1(a). One L1 node is connected to several L2 ring networks. The L2 nodes can serve traffic for business VPN, residential network connectivity and cellular networks. In such highly connected metro network, wavelength selective switches (WSS) play a crucial role in enabling dynamic connectivity [2]. Wavelength selective switches enable switching an incoming WDM signal of a wavelength channel to any output port. The capability to add or drop any wavelength switch at demand to and from any direction without contention enabled by WSS is used to realize colour-less, direction-less and contention less (CDC) ROADM add/drop functionalities as required in a flexible metro network [3,4]. Furthermore, the need for optical to electrical or electrical to optical conversion is removed thereby creating transparent optical networks.

The design of WSS involves a dispersive element to de-multiplex the WDM signal to the separate channels, a switching element to pass/block the channels and a multiplexing element to collect the WDM channels to the respective output port. A WSS design based on a *broadcast and select* architecture of an *N*-channel 1x*M* WSS consists of *M* wavelength blocker (WBL) modules as shown in Fig.1(b). The input signal is broadcast into *M* paths using a 1x*M* splitter. The broadcasted WDM signal is passed or blocked at each of the respective WBL modules. A single wavelength blocker module consists of a 1x*N* demultiplexer, *N* switches and *N*x1 multiplexer. The number of gate switches in a 1x*M* WSS is *MN*. Photonically integrated WSS implementation is advantageous due to low-cost related with mass production, compactness leading to easier integration as opposed to expensive free-spaced based WSS such as the ones based LCOS and MEMS mirror. Several implementations of WSS across platforms have been reported. Si based WSS have a potential for large scale implementation in scaling of wavelength channels and port numbers however performance is deteriorated from poor extinction ratio and large insertion losses. Researchers in [5] demonstrated SiPh 1x2 WSS based on the use reflectors and phase shifters to direct the wavefront toward the desired output port, however high insertion loss and poor extinction ratio were limiting factors. WSS demonstration with flexible spectrum allocation based on Si_3N_4 Mux/deMux AWGs and SiPh Mach-zehnder gate switches is given in [6], however performance is limited by large insertion losses. InP WSS based implementations [8, 9] include semi-conductor optical amplifier (SOAs) serving both as gate switches and booster amplifiers. Therefore, these switches have low-insertion losses and high extinction ratios.

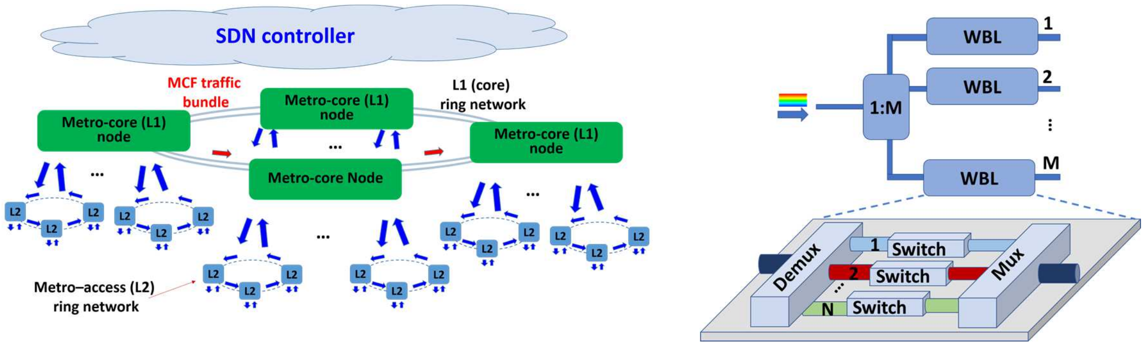


Figure. 1 (a) Schematic of SDN enabled L1(Metro core) node and L2 (Metro-access) ring networks (b) schematic of a 1xN WSS

However, the maximum port size is limited by wafer size, scalability in this case can be achieved by using modular implementation. On the other hand, hybrid approach enables the advantages of both SiPh and InP platforms for realizing low-loss, dense channel high port count WSS [10].

In this paper, we present the PASSION approach for implementing integrated WSS for enabling dynamic reconfigurability within a ROADM node for efficient utilization of network resources. Specific WSS designs proposed in the PASSION projects and its modularity in meeting high capacity demands are discussed. Experimental verification on a proof-of-concept SiPh/InP WSS implementation is presented.

II. METRO-CORE AND ACCESS SWITCHING NODE: THE PASSION APPROACH

In PASSION, we target the development and deployment of fundamental photonic technologies to support agile metro networks, capable of enabling target capacities of 8 Tb/s per fibre per single polarization, over 160 spectral channels. The implementation of the metro-core and access nodes is tackled via a modular implementation in a pay-as-you-grow manner. This paper focuses on the modular implementation of photonic integrated WSS within PASSION project. The proposed novel ROADM architecture for a metro-core L1 node is shown in Fig. 2(a). The L1 node is a high capacity ROADM node which is equipped with color-less, direction-less, and contention-less (CDC) capability and can transparently switch space division multiplexed (SDM) systems via *Fan-out* and *Fan-in* of multi-core fibre (MCF) bundles.

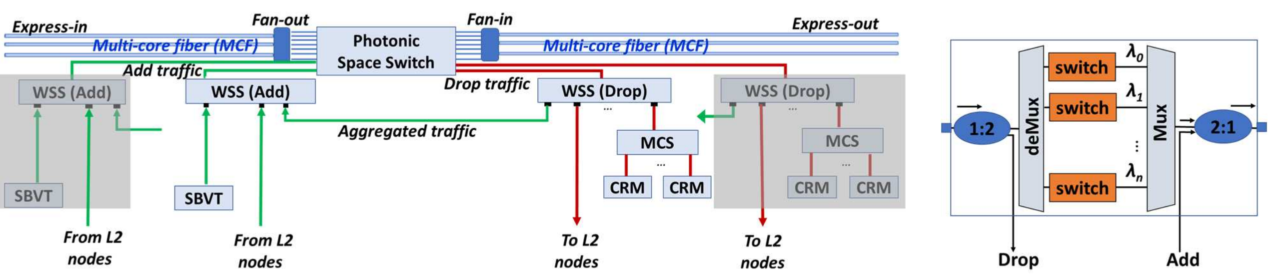
The photonic space switch, being the centre of the switching node, handles the traffic flow in the spatial domain in the *express-in/out* path. As such it forwards an incoming *express-in* traffic either directly as *by-pass* traffic or forwards the incoming traffic to disaggregate switch in the drop path as *Drop* traffic. Similarly, it forwards *Add* traffic in the *express-out* path. The wavelength selective switch (WSS) in the *drop/add* path functions as a disaggregating and aggregating switch respectively. Traffic with common destination are bundled and forwarded in the *express-out* path so that at the next L1 node, express ports can transparently direct the traffic without any process, saving resources and power consumption.

On the other hand, the L1 node enables adding/dropping of traffic from/to L2 (access) ring network. Furthermore, local add/drop functionalities at L1 node are embedded at the WSS in the *add* direction via sliceable bandwidth variable transmitters (SBVT) and in the *drop* direction via multi-cast switches (MCS) and coherent receiver modules (CRM). As the network grows, the new modules (shaded in grey boxes) are added in the *drop* and *add* directions to meet capacity demands.

The access (L2) nodes are low-cost 2-degree ROADM nodes with *add/drop* and wavelength blocker (WBL) functionality as shown in Fig. 2(b). The *add* and *drop* functionality are implemented with power splitter (for the *drop*) and power combiner (for the *add*). Wavelengths which are locally dropped are blocked by the WBL and the remaining wavelengths pass through WBL. The switches are implemented via SOA switching gates.

III. WSS DESIGN FOR METRO CORE NODE

In this section, the PASSION approach for modular integration of WSS is discussed. The first integration approach is monolithic based on Indium Phosphide (InP) and



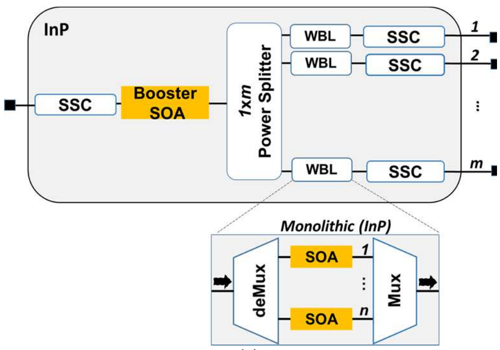
(a) (b)

Figure. 2 Modular architecture of PASSION (a) metro-core (L1) switching node with components: photonic space switch, wavelength selective switch (WSS), multi-cast switch(MCS) and Coherent receiver modules (CRM), slicable bandwidth variable transmitter (SBVT) (b) metro-access (L2) switching node.

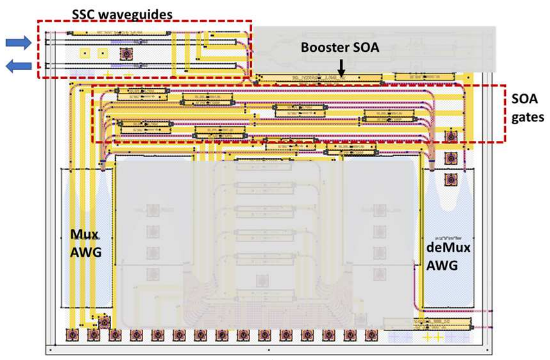
the second one is hybrid integration of low loss Silicon photonics (SiPh) passives integrated with InP SOA actives via flip chip assembly.

A. Monolithically integrated WSS based on InP

To realize low-loss operation, the monolithic approach relies on the on-chip amplification of semi-conductor optical amplifiers (SOA) combined with the low-loss coupling to SSMF via the use of spot-size converter (SSC) waveguides [11]. The schematic representation of the monolithic *n*-channel, 1x*m* WSS modules are given in Fig. 3(a). The design is based on *broadcast-and-select* scheme, in which the WDM signal is broadcast by a 1x*m* splitter and is selected by *m* wavelength blockers (WBLs) at the output ports. The WBL is constituted by de-multiplexing/multiplexing circuitry and SOA switching gates of the *n* wavelength channels. The SOA switching gates are used to pass/block the desired wavelength at each of the output ports. In case of monolithic integration, SSC waveguide is used at the input/output facets to minimize fibre-to-chip coupling losses. A booster SOA is used to compensate on-chip losses of passive circuitry. PIC design of monolithically integrated WBL for *m*=1, *n*=8, at channel spacing of 100 GHz is designed. The mask layout of this circuit is shown in Fig. 3(b).



(a)

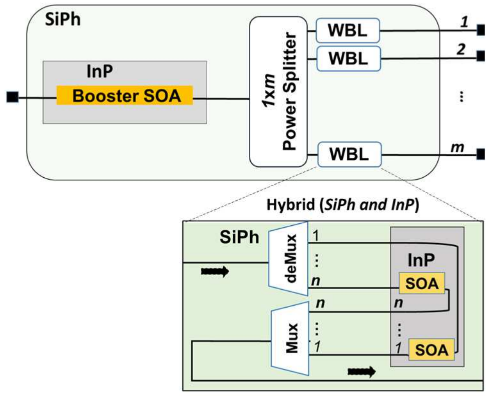


(b)

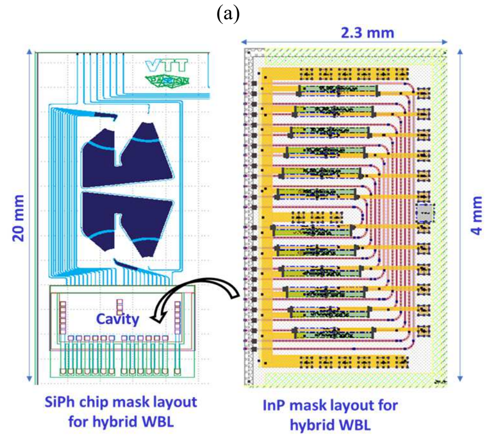
Figure 3 (a) Schematic of 1x*m* WSS module with *n* WDM channel (b) mask layout of a monolithic WBL (module) on InP

B. Hybrid design based on SiPh/InP

The schematic representation of the SiPh/InP hybrid integrated *n*-channel, 1x*m* WSS modules is given in Fig. 4(a). The design is based on *broadcast-and-select* scheme. The implementation of hybrid integrated WSS involves the integration of all passive circuitry (splitter, deMux/Mux AWGs) on low-loss SiPh platform while the SOA arrays are put on the InP chip. PIC design for the realization of a hybrid integrated WBL for *m*=1, *n*=10, at channel spacing of 100 GHz is conducted. The SOA switching gates on InP are



(a)



(b)

Figure. 4 (a) Schematic of hybrid integration of 1xm WSS SiPh passives and InP actives (b) mask layout of SiPh chip and zoomed out InP chip for hybrid WBL integration

placed in a U-shape where the input/output waveguides accessed from the same side. The mask layout of the designed SiPh and InP chips is shown in Fig. 4(b). In the SiPh chip, in addition to the deMux/Mux AWGs, cavities are designed which will be used for placing the InP chip during the flip-chip bonding assembly.

C. Modular implementation of WSS

The presented WBL design both on monolithic InP and hybrid SiPh/InP can be deployed to meet the capacity demands of the metro-core node as proposed in the PASSION project. As discussed in section 2, PASSION project targets capacity up to 8 Tb/s per fibre per polarization over 160 spectral channels within the C-band with a grid of 25 GHz spacing. The high capacity metro-nodes need to have the capacity to route any of these 160 spectral channels. The wavelength assignment is such that 40 wavelength channels with a spacing of 100 GHz span the C-band. A switching element containing several submodules covering the forty 100 GHz spaced wavelength channels is defined as a module.

TABLE I
NUMBER OF SUBMODULES AND MODULES OF WSS

Implementation	#of wavelength channels within submodule (WBL)	# of sub modules within a module	# of submodules in a 160 channel 1x16 WSS
Monolithic	8	5	5x4x16
Hybrid	10	4	4x4x16

Four of these modules with a relative shift of 25 GHz (0.2nm) in the centre wavelength result in 160 wavelength channels within C-band. Table.1 presents the required number of submodules for both monolithic and hybrid designs for covering 160 spectral channels. The realized wavelength blocker sub modules described in section 3 are used to calculate the numbers given in Table 1.

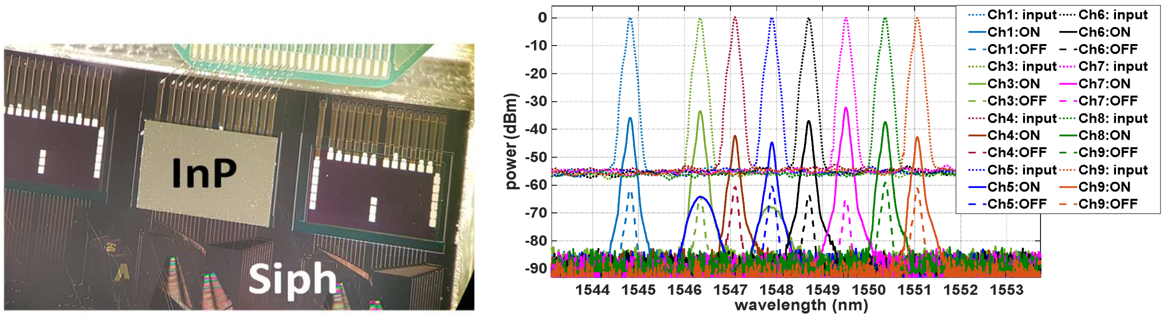
IV. EXPERIMENTAL VALIDATION

The hybrid WBL design presented in Section 3.2 is assembled via flip-chip bonding upon fabrication and the photograph of the assembled hybrid WBL is given in Fig.5(a). Fibre-to-fibre transmission tests and data transmission tests at 20 Gbps NRZ data were conducted and results validate the feasibility of the hybrid integration approach. Out of the 10 wavelength channels, 8 channels Ch1, Ch3, …, Ch9 are working. Fig. 5(b) shows transmission characteristics of eight wavelength channels when the SOA gates are *On/Off* for an input optical power of 0 dBm. Solid lines represent the WBL output when the gate SOA is *On* state and dashed line shows the WBL output when the gate SOA is in the *Off* state. Typical measured *On/Off* ratio is around 30 dB. The fibre-to-fibre losses for Ch1, Ch3, Ch6, Ch7, Ch8 range from 32.2 to 37.5 dB. The current for each gate SOA is optimally tuned to minimize both the fibre-to-fibre loss and the effect of back reflection on the hybrid WBL. Accounting for 2.5 dB insertion loss per AWG and 3 dB/facet for chip-to-fibre coupling losses, 3 dB gain of the SOA at 40 mA, the best channel Ch3 has 12 dB/facet hybrid coupling loss: resulting excess loss of 9dB/facet. We believe the measured excess losses are the result of tight alignment tolerance which can be relaxed by using on-chip integrated spot-size converters [10]. In our future implementation, we also plan to use angled waveguides to alleviate the impact back reflection and fully employ the gain of SOAs. Table. II summarizes the fibre-to-fibre loss of each channel, and the corresponding current of the SOA gate. Fig. 6(a) shows the gain characteristics of the gate SOA for Ch3 for varying current (mA) and varying input power. It is shown that fibre-to-fibre loss varies from 60 dB at the absorption state of the SOA at 0 mA to 26 dB due to gain provided by the SOA at 100mA. The fibre-to-fibre loss is in the order of 33 dB at 80 mA for all input power values. The loss decreases to 26 dB at SOA current of 100mA; for input power of 0 dBm and -5 dBm. Effects of SOA saturation on the fibre-to-fibre loss is slightly observed at 100 mA for input power of 7 dBm and 10 dBm resulting fibre-to-fibre losses of 29 dB and 31.57 dB respectively.

TABLE II
FIBER-TO-FIBER INSERTION LOSS

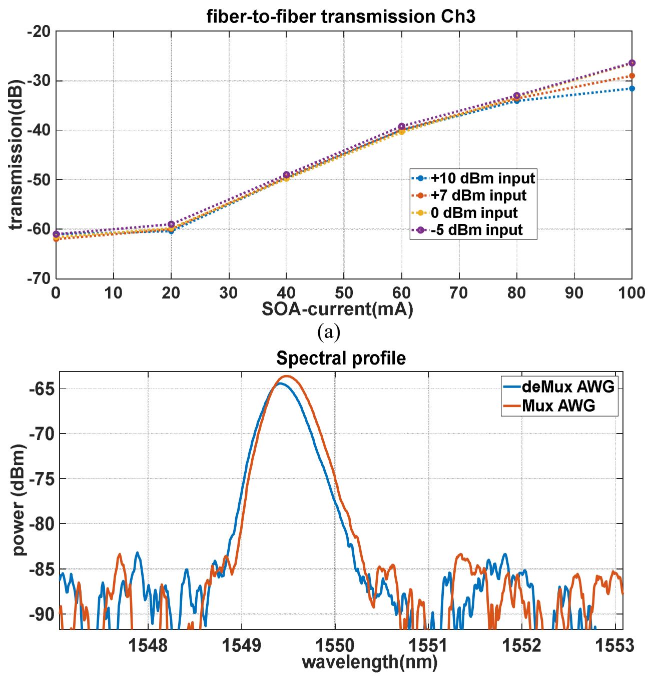
Ch #	1	3	4	5	6	7	8	9
Fiber-to-fiber loss (dB)	36	33.4	42.3	44.8	37.0	32.2	37.5	42.8
SOA current (mA)	40	80	80	80	90	40	80	28

Next, the 3dB bandwidth of *deMux* and *Mux* SiPh AWGs was measured. The 3dB bandwidth was measured to be 50 GHz and matches the design specification. It was further observed that the deMux/Mux AWGs have a good central wavelength channel matching; for instance, Ch7 has a relative shift of only 0.07 nm between deMux and Mux AWGs as illustrated in Fig. 6(b).



(a) (b)

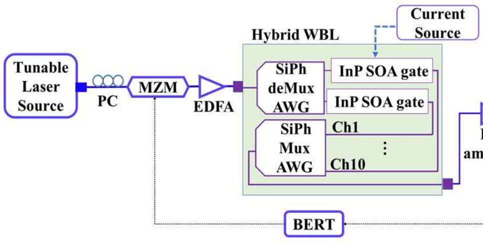
Figure 5 (a) photograph of hybrid integrated WBL submodule (b) Input optical signal (*dotted line*), output optical signal of the Hybrid WBL switch ON (*solid line*) /Off state (*dashed line*)



(b)

Figure 6 (a) fiber-to-fiber transmission and gain characteristics of SOA (Ch3); (b) AWGs spectral profile, collected ASE (SOA) from Ch7

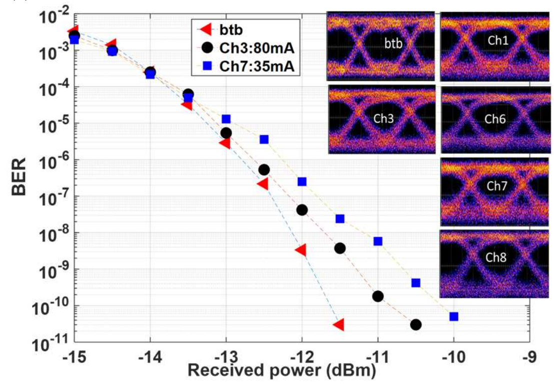
Fig. 7(a) shows the experimental setup for data transmission of 20 Gbps NRZ 2^{31}-1 PRBS data. A tunable laser source is used to generate light for wavelengths corresponding to the channels of the WBL. Lensed fibres are used to couple light in/out of the hybrid WBL switch. The input optical modulated data was boosted to 17 dBm to compensate the losses in hybrid WBL. After transmission through the WBL, a second preamplifier is used to reach the



(a)

Channel	Penalty (dB) at 1E-9	Current (mA) of SOA
Ch1	1.3	35
Ch3	0.7	80
Ch6	2	90
Ch7	1.4	35
Ch8	2.8	60

(b)



(c)

Figure 7 (a) Experimental setup for data transmission of 20 Gbps NRZ 2^{31}-1 PRBS (b) BER penality at 1E-9 for each channel (c) BER vs received power for Ch3 and Ch7 and eye diagram for all channels

sensitivity of the 20Gbps receiver. A bandpass filter (BPF) with 3 dB bandwidth of 200 GHz is used before the receiver. Error free transmission is achieved for Ch1, Ch3, Ch6, Ch7, and Ch8. The penalties range for 0.7 dB in case of Ch3 and 2.8 dB in case of Ch8 at BER value of 1E-9 as tabulated in Fig. 7(b). The current of the SOA for each channel is optimized to minimize power penalties. Fig. 7(c) shows the plot of BER vs received power for 20 Gbps transmission for two channels (Ch3 and Ch7) and clear eye diagrams of five channels.

These successful data transmissions through the modularly designed hybrid WBL verify its feasibility to be used in high capacity metro-core switching node where capacity can be scaled by adding new modules in a pay-as-you-grow manner.

V. CONCLUSIONS

In this paper, we introduced the modular integration of both monolithic and hybrid of wavelength selective switches to be used in high capacity metro-core and access network. The PASSION approach for realization of high capacity metro-core nodes and low-cost metro access nodes is presented. The modular design of both monolithic and hybrid wavelength selective switches allows to cover 160 wavelength channels with spacing of 25 GHz within the C-band. Experimental validation of hybrid integrated WBL consisting of passive Mux/deMux AWGs in SiPh and InP gate SOAs aligned and assembled via flip-chip bonding is presented and results confirm the feasibility of the proposed WSS design approaches. The first trial assembly process is followed by on-going efforts to reduce excess hybrid coupling losses via optimization of the flip-chip assembly process, the use of on-chip spot-size converter to relax tight alignment tolerances, and by employing angled waveguides at the facets to reduce back reflection. The demonstrated error free transmission of 20 Gbps per wavelength channel opens to modular and scalable switching functionality, which is pivotal for next generation modular metro-networks.

ACKNOWLEDGMENT This work is funded by the EU H2020 programme, PASSION project GA 780326.

REFERENCES

[1] N. Calabretta et al, “Photonic integrated WDM crossconnects for metro and data center networks,” SPIE 2019, San Francisco, California

[2] Svaluto Moreolo, M.; Fàbrega, J.M.; Nadal, L. Sliceable BVT Evolution Towards Programmable Multi-Tb/s Networking. *Electronics* 2019, *8*, 1476. ‘

[3] A. Devarajan, K. Sandesha, R. Gowrishankar, B. S. Kishore, G. Prasanna, R. Johnson, and P. Voruganti, “Colorless, directionless and contentionless multi-degree ROADM architecture for mesh optical networks,” in Proceedings of 2010 Second International Conference on Communication Systems and Networks (IEEE, 2010), pp. 1–10.

[4] 4. H. Yang, B. Robertson, P. Wilkinson, and D. Chu, “Low-Cost CDC ROADM Architecture Based on Stacked Wavelength Selective Switches,” J. Opt. Commun. Netw. 9(5), 375–384 (2017).

[5] Fumi Nakamura, Kyosuke Muramatsu, Keijiro Suzuki, Ken Tanizawa, Minoru Ohtsuka, Nobuyuki Yokoyama, Kazuyuki Matsumaro, Miyoshi Seki, Keiji Koshino, Kazuhiro Ikeda, Shu Namiki, Hitoshi Kawashima, and Hiroyuki Tsuda, "Integrated silicon photonic wavelength-selective switch using wavefront control waveguides," Opt. Express 26, 13573-13589 (2018)

[6] C. R. Doerr, L. L. Buhl, L. Chen, and N. Dupuis, “Monolithic flexible-grid 1× 2 wavelength-selective switch in silicon photonics,” J. Lightwave Technol. 30(4), 473–478 (2012).

[7] N. Tessema et al., "SDN enabled dynamically re-configurable low-cost ROADM nodes for metro networks," OECC/PSC 2019.

[8] K. Prifti, X. Xue, N. Tessema, R. Stabile and N. Calabretta, "Lossless Photonic Integrated Add-Drop Switch Node for Metro-Access Networks," in IEEE Photonics Technology Letters, vol. 32, no. 7, pp. 387-390, 1 Aprill1, 2020, doi: 10.1109/LPT.2020.2975885

[9] R. Stabile et al. “Monolithically integrated 8×8 space and wavelength selective cross-connect,” JLT. 32(2), 201–207 (2013).

[10] T. Matsumoto et al., "Hybrid-Integration of SOA on Silicon Photonics Platform Based on Flip-Chip Bonding," in JLT 2019

[11] Y. Ueda *et al*., "Compact InP spot-size converter with vertically tapered core layer formed by micro-loading effect," in *Electronics Letters*, vol. 53, no. 12, pp. 797-799, 2017