Guest Editorial: Multi-Band Optical Networks

AS GUEST EDITORS we are pleased to present this Special Issue of the JOURNAL OF LIGHTWAVE TECHNOLOGY devoted to multi-band optical networking. The goal is to introduce the key challenges, trends, and innovations.

Current deployed networks (e.g., for backbone and metro) are reaching the saturation of their capacity with the continuous bandwidth demand increase. However, the installation of new infrastructures or fibers requires high investments from network operators. Thus, alternative solutions to cope with the enormous bandwidth demand are needed. Currently, single-mode fibers (SMF) are mainly used in the C band, where SMFs present the minimum attenuation. The exploitation of other bands (e.g., L, S, E and O) may be an effective solution for network upgrade while postponing the installation of new fibers. As L-band technologies are widely deployed today, there is a rising interest in considering other optical bands (e.g., S and E) in the following years to scale capacity. Multi-band (MB) optical networking is therefore feasible considering that many of the currently deployed fibers (e.g., G.652.D fibers) do not present the absorption peak (occurring mainly in the E band).

However, several issues still need to be considered and addressed. First, the enabling technology does not support networking in all the bands (e.g., transceivers or wavelength selective switches – WSSs) yet. Second, Stimulated Raman Scattering (SRS) effect becomes highly relevant in MB networks generating a power transfer from lower-wavelength channels to higher-wavelength channels. Thus, lower-wavelength channels may be dominated by amplified spontaneous emission, while non-linear impairments may be highly detrimental for higher-wavelength channels. In this context, quality of transmission (QoT) estimation, as well as connection provisioning and control, should be refined in order to account for such an effect. Other open issues also concern the definition of network architecture, network optimization, automation, control plane and programmability of devices operating in the bands beyond C, processing of monitoring information, and operation, administration and maintenance.

In this Special Issue, we received 21 manuscripts from the open call and also invited 5 distinguished groups representing the view of network operators, vendors, and academia researchers as the leading edge technologies of the field. From all the submitted manuscripts including the invited ones, we selected, with the assistance of an international team of expert reviewers, a total of 14 articles for publication in this Special Issue. Our objective for the paper selection is to represent the breadth and depth of the topic accounting for the trends driven by research working towards multi-band optical networks, ensuring only the highest quality results. The contributed papers in this Special Issue cover a wide variety of topics, representing a broad mixture of network architecture, transmission modeling, enabling technology, performance monitoring, control plane, implementations, and experiments.

The paper "Solving for Scalability from Multi-Band to Multi-Rail Core Networks" by R. Schmogrow presents the view of a network operator on the capacity increase. The paper discusses the opportunity, implications, and challenges of capacity scaling considering three dimensions: spectral efficiency optimization through signal-to-noise ratio optimization, the exploitation of multi-band, and the use of space division multiplexing (SDM) (e.g., parallel fiber systems). The paper also presents network architectures and performs numerical simulation study, showing the capacity benefits offered by the utilization of additional transmission bands, while assessing that multi-rail or SDM networks are expected to be deployed in longer terms.

Then, the Special Issue proceeds with the view of a vendor, with the paper "Challenges and Enabling Technologies for Multi-Band WDM Optical Networks" by N. Deng *et al.*, investigating the challenges of the enabling technologies. In particular, optical amplification, WSSs, and optical amplifiers to mitigate SRS effect are presented. The paper proposes a hybrid optical amplifier based on erbium-doped fiber and bismuth-doped fiber operating in a single stage over 100-nm band. Then, the authors present a design for an LCoS-based 2×35 WSS operating over 100-nm band. Finally, an amplifier embedding an optical spectrum processor is presented showing WDM channel equalization with the ability of limiting detrimental SRS effects. Different from equalization provided by WSSs, such a device allows to equalize the channels on a per span basis achieving almost flat OSNR after 8 spans.

The paper "PPLN-based Optical Parametric Amplification for Wideband WDM Transmission" by S. Shimizu *et al.* presents an overview, as well as the effort of an operator, on optical parametric amplification applied to multi-band networks. Optical parametric amplifiers may have several use cases, such as wideband inline amplification, wavelength conversion, fiber-nonlinearity compensation, and phase-sensitive amplification. A 10-THz-class inline amplification and simultaneous inter-band wavelength conversion based on Periodically poled Lithium Niobate (PPLN) is then presented.

The paper "On-chip Waveguide Amplifiers for Multi-band Optical Communications: A Review and Challenge" reviews on-chip broadband waveguide amplifiers. The authors assess that at the moment no single rare-earth-doped fiber can provide optical amplification covering from U to O band. Er-doped waveguide

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amplifiers for C and L bands, Nd-doped waveguide amplifier for O and E bands, and the Tm3+-doped waveguide amplifiers for S and U bands are reviewed.

The paper "Characterization, Monitoring, and Mitigation of the I/Q Imbalance in Standard C-Band Transceivers in Multi-band Systems" by G. Di Rosa *et al.* focuses on transceivers operating on a S+C+L-band system. The authors assume in-phase/quadrature (I/Q) modulator designed for the C-band and investigate the wavelength-dependent I/Q imbalance of such modulators when they operate on a S+C+L-band system. The transceiver impairments are monitored and may be mitigated, based on wavelength-independent calibration and digital signal processing (DSP) demonstrating the operability of commercial transceivers optimized for the C band in multi-band networks.

The paper "Multi-band operation of flat-top supercontinuum laser sources with programmable repetition rate up to 50 GHz" by Chengliang Zhang *et al.* proposes supercontinuum sources with multiband coverage by merging high-repetition-rate electro-optic frequency comb techniques with optical line-by-line pulse shaping. Experimental results for a smooth flat-topped comb with a 10-dB 97 nm bandwidth from the L- to the S-band are presented with excellent stability over a 3-hour time window. The presented results open new possibilities for generating robust and coherent multiple optical carriers also in multi-band transmission scenarios.

The paper "Ultrawide-band Low Polarization Sensitivity 3-μm SOI Arrayed Waveguide Gratings" presents an ultrawide-band (UWB), O- to L- band, polarization insensitive (PI) 1×12 100 GHz channel spacing arrayed waveguide grating (AWG) designed and realized in 3-μm Silicon-on-Insulator (SOI) platform. PI and UWB operations are achieved by directly exploiting the UWB 3-μm PI silicon waveguide as the arrayed waveguide. The PI AWG can be employed as demultiplexer and multiplexer in photonic integrated circuits (PIC)s, such as UWB wavelength selective switches (WSS)s. Experimental results demonstrate UWB (O- to L- band) and PI 1×12 AWG operation with -0.82 dB to -1.52 dB insertion losses, < -35 dB average cross-talk, 0.18 dB to 1.27 dB polarization dependent loss (PDL), and 0.006 nm to 0.041 nm polarization dependent wavelength shift (PDWS). Error-free operation at 10^{-9} BER were measured with power penalties <0.1 dB, <0.2 dB, and <0.8 dB for 10 Gb/s, 20 Gb/s and 35 Gb/s NRZ-OOK PRBS 2^{31}-1 multi-band data, respectively.

The paper "Scalable and Disaggregated GGN Approximation Applied to a C+L+S Optical Network" by A. D'Amico *et al.* focuses on transmission modelling for L+C+S networks. The authors propose an approximation of the Generalized Gaussian Noise (GGN) model including the SRS effect for QoT estimation in multi-band networks. The proposed semi-analytical solution is shown to provide QoT estimations with a maximum error of 0.3 dB in the considered scenario, highlighting that the proposed approximation is conservative and computationally fast.

The paper "Optical Layer Impairments and Their Mitigation in C+L+S+E+O Multi-Band Optical Networks with G.652 and Loss-Minimized G.654 Fibers" by Minje Song *et al.* analyzes the effect of multi-band transmission on both standard single-mode and cut-off shifted single-mode optical fibers. Specifically, the additional impairments caused by the multi-path interference (MPI) resulting from the interplay between the fundamental LP01 mode and the high-order LP11 mode is considered together with the impact of ASE noise and nonlinear interference, considering the Stimulated Raman Scattering. The Authors present an extensive set of experimental results and propose a model for the assessment of multi-band transmission capacity. Then, they derive and present design and planning results for different transmission scenarios, commenting on the dominant transmission impairments, depending on the fiber type.

The paper "Survivable Routing, Spectrum, Core and Band Assignment in Multi-Band Space Division Multiplexing Elastic Optical Networks" assumes multi-band transmission over SDM optical networks based on multi-core fibers. In this context, the authors present routing, core, spectrum, and band assignment for working and protection resources, while accounting for SRS. Both integer linear programming and heuristic are proposed. The combined use of MB and SDM can strongly increase the supported network capacity.

The paper "SNR Re-verification-based Routing, Band, Modulation, and Spectrum Assignment in Hybrid C-C+L Optical Networks" by Q. Yao propose routing, band, modulation, and spectrum assignment, while accounting for SRS, e.g., generated by new requests on existing requests. The re-verification of SNR is implemented to verify that the QoT of existing lightpaths does not become unacceptable due to the SRS effect induced by new requests.

The paper "Transparent vs Translucent Multi-band Optical Networking: Capacity and Energy Analyses" by R. Sadeghi presents an analysis on the capacity increase and energy consumption of U+L+C+S systems applied to transparent and translucent networks. The use of regenerators deployed in translucent networks may significantly increase network capacity (e.g., given that high-order modulation formats are more likely used) at the expense of more interfaces. However, the activation of an additional band in transparent networks brings to performance in terms of capacity comparable with the one of a C-band-based translucent network without the need of costly additional interfaces.

The Special Issue next proceeds with an SDN-controlled sliceable transponder for multi-band networks, "SDN-enabled Multi-band S-BVT within Disaggregated Optical Networks" by L. Nadal *et al.* An L+C+S scenario is considered and SDN control is adopted to automate the configuration of transceivers, allowing to enable/disable several channels supported by the transponder, working within the different bands, exploiting a flexible and modular architecture adapted to the network status.

Finally, the paper "DSP-based Link Tomography for Amplifier Gain Estimation and Anomaly Detection in C+L-band Systems" by R. Sena *et al.* deals with performance monitoring in multi-band optical networks. A tomography technique is proposed to estimate the spectral gain profile of a C+L-band in-line amplifier and to detect anomalies in amplifications, such as gain tilt and narrowband gain compression. A sub-dB accuracy is achieved in the adopted experimental setup. The proposed approach can find application in vendor-neutral networks by characterizing in-line components regardless of the availability of information provided by vendors.

In preparing this Special Issue we have benefited greatly from the advice of many distinguished researchers in the field of optical networks. We would also like to thank Gabriella Bosco, Editor in Chief of the JOURNAL OF LIGHTWAVE TECHNOLOGY, for offering us the opportunity to publish this Special Issue, and Douglas Hargis and Sonal Parikh, publication administrators, for their great efficiency and helpfulness. We are also very grateful to the community of reviewers for their excellent contributions and their willingness to provide detailed technical feedback within a tight time schedule, which made our work much easier. Finally, we would like to thank all the authors for their support of the Special Issue, specifically for the submission of papers of outstanding archival quality and for their cooperation in meeting deadlines so as to meet the scheduled publication date. We hope that this Special Issue will provide a timely snapshot of the state of the art in multi-band enabling technologies and networks.

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