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Session Title	High Capacity Transmission	**Session Code**	5B3
Date & Time	July 5 (Thu.) / 14:00-15:30		
Place	Room B (Samda Hall B)		
Session Chair	Inwoong Kim (Fujitsu Lab of America)		

5B3-1 (Paper No. SC2_1076) | Invited | 14:00-14:30 (30')

Perspectives of Multi-Band Optical Communication Systems

Antonio Napoli[1], Nicola Calabretta[2], Johannes K. Fischer[3], Nelson Costa[4], Silvio Abrate[5], Joao Pedro[1], Victor Lopez[6], Vittorio Curri7, Darko Zibar8, Erwan Pincemin9, Sebastien Grot[1]0 , Günther Roelkens[11] , Chris Matrakidis[12] , Wladek Forysiak[13]
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5B3-2 (Paper No. SC2_1089) | Invited | 14:30-15:00 (30')

Multi-Dimensional Modulation with Iterative Decoder for High Capacity Optical Transport Network

Masanori Nakamura, Fukutaro Hamaoka, Asuka Matsushita, and Yoshiaki Kisaka
NTT Corp., Japan

5B3-3 (Paper No. SC2_1049) 15:00-15:15 (15')

50.4 Tbit/s, 128 QAM L-band WDM Injection Locked Coherent Transmission over 160 km with Spectral Efficiency of 10.5 bit/s/Hz

Takashi Kan, Keisuke Kasai, Masato Yoshida, Toshihiko Hirooka, and Masataka Nakazawa
Tohoku Univ., Japan

5B3-4 (Paper No. SC2_1005) 15:15-15:30 (15')

Single-Channel 7.68 Tbit/s, 64 QAM Coherent Nyquist Pulse Transmission over 150 km with a Spectral Efficiency of 9.7 bit/s/Hz

Kosuke Kimura, Junpei Nitta, Masato Yoshida, Keisuke Kasai, Toshihiro Hirooka, and Masataka Nakazawa
Tohoku Univ., Japan

Perspectives of Multi-band Optical Communication Systems

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***Abstract*—In this paper, we discuss the state-of-the-art of components and technology to enable multi-band transmission over single mode fibers (SMFs). A full overview on the most relevant challenges is provided.**

I. Introduction

Telecommunication forecasts highlight a yearly bandwidth growth between 20% to 60% [1]. This trend will be further fueled by upcoming innovations such as 5G and high-capacity access networks. At the same time, power consumption and cost per bit must be reduced. Additionally, service providers want to extend the usage of existing optical. Multi-band (MB) transmission is a promising strategy to fulfill these requirements, aiming at transmitting over the entire SMF spectrum (see Fig. 1). This will extend the system capacity and thus postpone new fiber deployment. Although the optical fibers can be re-used, all components and network element beyond C-band must be designed to work in a MB environment. In some cases, the technology is already available [2]. Additionally, we conjecture the effort to adapt digital signal processing (DSP) algorithms [3] and network management, designed for C-band, to MB systems should be marginal. Due to the current existing amplification technology, we believe that a first application of this concept would be for data-center interconnect (DCI) with distance ≤ 80 km. In a second moment, with increasingly mature devices, metro-aggregation network could also become a potential use case.

II. When will the operators need to upgrade?

To cope with the continuous bandwidth growth, operators can deploy novel fiber infrastructures or upgrade their networks. In some cases, the first option is not available, because fiber might be only leased, because of local regulations. Moreover, it is highly desirable to better exploit the large investments made over the last decade. These boundary conditions make the components cost marginal when the fiber cost is included in the total-cost-of-ownership (TCO) equation [4]. Despite the high effort to increase fiber availability, some operators agree that the current deployed capacity might be soon not sufficient anymore, especially for the case of metro/DCI applications where most of the traffic is now concentrated. In this context, the extension of C-band transmission is an extremely valuable asset. The first step toward MB transmission is represented by C+L-band systems which are being currently deployed for submarine applications to extend the cable life-time. The following natural step would be to consider the remaining low-loss bands of SMF.

Name	O	E	S	C	L
Wavelength range (nm)	1260-1360	1360-1460	1460-1530	1530-1565	1565-1625
C-band system				35 nm	
C+L-band system					95 nm
Average fiber loss (dB/km)	0.36	0.28	0.22		0.18
Multi-band			365 nm		

Fig. 1. Low loss transmission bands of single mode fiber.

III. Technology options and requirements for MB

a) Multi-band coherent transceiver front-ends: Current commercial optical coherent transceiver front-ends mainly target C- or L-band operation. Mach-Zehnder modulators are available also for the O-band. However, for cost-efficiency and simpler MB networks management and operation, it would be desirable to employ coherent transceivers capable of transmitting over the entire MB wavelength range of 365 nm. Not only would this reduce the cost of manufacturing the photonic integrated circuits (PICs) due to a single one-size-fits-all design (i.e., mass production), but it would also simplify stock-keeping and reduce maintenance costs. The potential to realize such ultra-wideband operation was demonstrated in [2] with silicon PICs. In principle, InP-based modulators and coherent receivers may also be adapted to achieve operation from O- to L-band. The main challenge to achieve this goal is in the design of multi-mode interference couplers which currently exhibit significant dependence of insertion loss and splitting ratio with wavelength. In conclusion, there is promising potential for cost-efficient MB coherent transceivers based on different material systems with silicon PICs spearheading the ongoing evolution.

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b) Multi-band laser sources: Epitaxial layer structures typically provide sufficient gain to cover a 50-100 nm wavelength range, which means that multiple active layer stacks need to be combined in a single transmitter to cover the entire MB wavelength range. An elegant approach to realize MB lasers consists in assembling the active layer stacks on a single PIC by means of transfer printing [5], which is a cost-effective approach to densely integrate different epitaxial layer stacks. When integrating these gain materials on a silicon photonic waveguide platform, we can make use of the high-quality filters that are available on this platform to realize narrow linewidth widely tunable lasers [6]. As each of the lasers can cover only part of the MB spectrum, a broadband optical switch can be used to couple a particular laser to the single mode fiber.

c) Multi-band optical amplifiers: There are different strategies for MB amplifiers: (I) optimize them for each band (to enable a pay-as-you-grow approach); (II) employ semiconductor optical amplifiers (SOA) that provide a wide spectrum, but where accumulated nonlinear penalty is still an issue [7]. In case of low cost short reach links, we might utilize doped fiber amplifiers (DFA) with, for example, the following doping materials: Praseodymium (O); Bismuth or Neodymium (E); Thulium (S); and Erbium (C+L). Current Erbium doped L-band amplifiers might provide amplification up to 1625 nm by jointly optimizing the doped fiber and the pumps. Another approached consists in employing Raman amplification, a well-established technology to deliver wideband optical amplification [8]. In this case, the gain profile is determined by the Raman gain spectra of multiple pump lasers [9], but to date their usage has been mainly restricted to augmenting the gain of C-band EDFAs for spans that are particularly lossy [10]. Though Raman amplifiers are commonly deployed for distributed amplification, wideband discrete Raman amplifiers have also been developed, in which the Raman pump light is provided to a dedicated Raman gain fiber located in an amplifier module at a network node [11]. These discrete Raman amplifiers do not offer the noise figure advantage of distributed amplifiers, and also introduce relatively long lengths of nonlinear Raman gain, but they avoid launching high pump powers into the transmission fiber, thus eliminating optical safety and fiber plant concerns. A dual-stage design can limit the transmission penalties due to Raman fiber nonlinearities while delivering the gain and output power required [12].

d) Multi-band wavelength selective filters: Modular MB wavelength selective filters (WSS) can be built out of PIC for WDM switches and filter modules operating in the different bands. The active/passive structures can be realized using: (I) passive WSS with electro-optical switches, where optical amplifiers compensate for the losses; (II) modular monolithic WSS PIC with more efficient voltage driven E/O switches for lower power consumption; or (III) heterogeneous integration on silicon photonics technology like for the MB tunable lasers. Fig. 2 shows the usage of MB-WSS to realize a MB-reconfigurable optical add drop multiplexer (MB-ROADM).

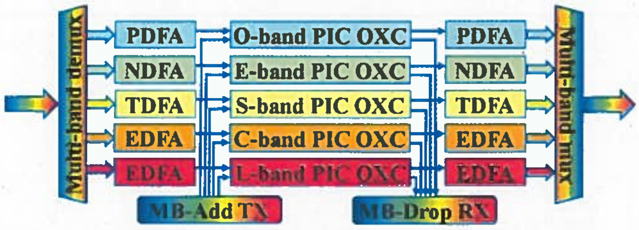

Fig. 2. Possible architecture for a MB ROADM.

e) Digital signal processing:: DSP will have a dual role in enabling MB transmission: (I) mitigation of fiber propagation effects over a broad band; (II) compensation of the MB component imperfections within the transceivers. However, we envision that limited changes should be needed in MB systems with respect to current commercial available DSP, in particular for short reach scenarios.

f) Network planning and management: Performance across the entire spectrum might be significantly different. This implies that a sophisticated optical performance model is required. If the *pay-as-you-grow* approach is adopted, the band upgrade must be carefully managed. This could be realized by employing more advanced (and thus complex) routing, channel format and spectrum assignment algorithms. State-of-the-art approaches exploring data analytics and advanced monitoring schemes can also be exploited for more efficient MB network planning and management.

IV. Conclusions

We reviewed the literature and provided the point of view of system vendors and global operators on the need of opening SMFs transmission beyond C-band. MB is a great opportunity, and if C+L-band transmission is the state-of-the-art, O- to L-band transmission is the future. We believe that this solution can find a first application in DCI, followed by metro to regional networks. Given the current reported transmission records, a MB approach might achieve a capacity in excess of 250 Tb/s over SMF for short reach scenarios. Additionally, MB enables the full exploitation of deployed optical fiber infrastructures, enabling a *pay-as-you-grow* approach requiring simultaneously only a incremental investment for the needed technology.

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