Key Enabling Technologies for High-Capacity Transport System with Channel Rate over Terabit per Second

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Abstract *This paper reviews the issues and challenge to realise high-capacity optical transport system with channel rate over Terabit per second. We describe both novel channel-bandwidth enhancement schemes for achieving an over-1-Tbps optical channel and optical signal bandwidth extension schemes beyond C+L band, respectively. ©2023 The Author(s)*

Introduction

Since the global data traffic generated in future 6G era will rapidly increase at the annual growth rate over 1.4 times/year, ever increasing demand for enhancing the high-capacity long-haul (LH) transport system is mandatory. In order to support such demand, 16-Tbps LH digital coherent transport system with the channel rate of 400 Gbps was installed into today's NTT group in 2020 as shown in Fig.1 [1]. Since the required total system capacity in terrestrial network will exceed 1 Pbps by 2030, scalable optical transport technologies are crucially needed to support high capacity over 1 Pbps.

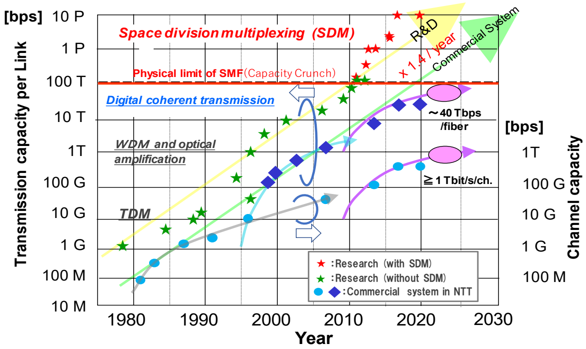

Fig. 1 Capacity Evolution and Future in NTT Group

It is important to extend the WDM signal bandwidth beyond the conventional C+L band for the next generation system based on single mode fiber (SMF). However, the existing SMF has a capacity limit of about 100 Tbps in future due to the Kerr nonlinear effect and the allowable input power limit from the viewpoint of laser safety, which is recognized as a capacity crunch. Various SDM optical transport schemes have been studied in order to deal with this problem fundamentally [2, 3].

In this paper, we describe key channel-bandwidth enhancement schemes for increasing the channel capacity scalable to the multi-Tbps level in future high-capacity LH wavelength division multiplexed (WDM) transport systems. Furthermore, effective combination of the novel ultra-wideband amplification and space division multiplexing (SDM) scheme are described as a key to extend the usable optical signal bandwidth scalable to several 100 THz, which is more than 10-times wider than that in C+L band, in future as shown in Fig. 2.

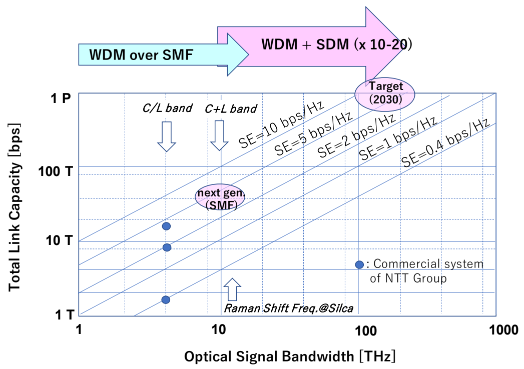

Fig. 2: Future bandwidth extension by WDM and SDM

Enhancement of channel rate over 1 Tbps

In the commercial market, the maximum channel rate of DSP-ASIC reached up to 1.2 Tbps. In order to achieve both the channel capacity exceeding 1 Tbps and a long-haul (LH) transport over 1000 km, it is necessary to expand the signal band and keep the spectral efficiency (SE) to some extent. For example, if the symbol rate can be increased to more than 200 GBd at 1.6 Tbps in future, it is possible to achieve LH transmission of 1000 km or more by keeping the SE around 5 bits/Hz, assuming FEC coding rate of about 0.8 and the passband narrowing by ROADM (see Fig. 3) [4].

In our previous works, an an Indium Phosphide (InP) hetero bipolar transistor (HBT) amplifier IC has potential to enlarge the baseband amplification bandwidth over 200 GHz [5], however, the usable bandwidth of the packaged amplifier IC is limited by the connector bandwidth less than 130 GHz [5]. Therefore, it will be rather difficult to implement low-distortion, high-efficiency implementation of a broadband baseband signal interconnection between these devices with connecter interfaces with the millimeter-wave bandwidth in future multi-Tbps class transceiver.

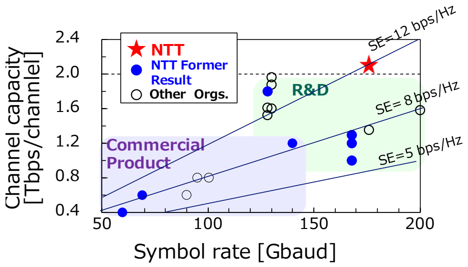

Fig. 3: Required SE and symbol rate for over-Tbps channel.

One of the effective schemes to solve this issue is an integration in optical frontend module that incorporates an analogue multiplexing (AMUX) and de-multiplexing function in the optical transmitter/receiver front-end circuit. In the literature [6], the InP in-phase/quadrature-phase modulator chip and the 2:1 analogue multiplexing circuit with built-in driver IC chip are all hybrid-integrated into one module in the digital coherent optical frontend circuit to mitigate the electrical-connector bandwidth limit as shown in Fig.4. At the same time, the digital signal processing of removing the linear and nonlinear distortion generated in such optical transmission/reception circuit is also key [7-12]. Using the integrated AMUX optical transmitter module, we have successfully achieved WDM transmission with the channel rate over 1 Tbps for the first time [10].

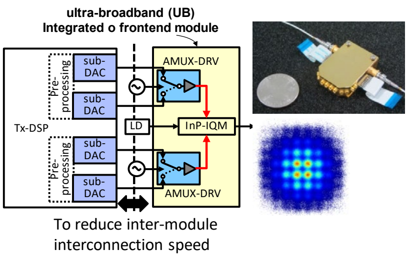

Fig. 4: Impact of device integration in optical frontend.

Moreover, the linear and nonlinear distortions in the transceiver tend to severely limit the operation speed and signal SNR in recent spectrally-efficient probabilistic constellation shaping high-order multilevel modulation. By enhancing the DSP compensation enhancement combined with optical spectral equalizer, 240-km inline amplified transmission with the channel rate over 2 Tbps was first demonstrated [11]. In order to further relax the bottleneck in electrical bandwidth limitation, direct optical spectrum synthesis called as spectral weaving is proposed for multi-Tbps channel [12]. Here the analogue multiplexing and de-multiplexing are conducted in the optical frequency domain using novel optical time division multiplexing based on an integrated modulators combined with digital signal pre-processing, and multi-Tbps signal generation can be expected by CMOS-based digital-to-analogue converters.

Extension of optical amplifier bandwidth

It is well known there is a trade-off between SE and transmission distance, Modulation format and forward error correction code are flexibly set to balance the SE and reach in future LH WDM transmission systems. Since the SE cannot greatly increase in future at multi-Tbps level, required signal bandwidth is proportional to the channel rate. For example, if the channel capacity is increased over Tbps-level while the SE is kept to around 5 bit/s/Hz, the required signal bandwidth of the 3.2 Tbps channel will be over 400 GHz. This naturally reduces the number of WDM channels accommodated in the C+L band to less than 20 as shown in Fig.5

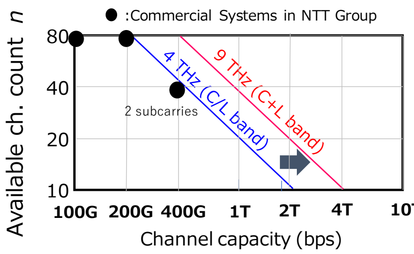

Fig. 5: Available number of WDM channels for over 1 Tbps channel assuming the SE of 5 bps/Hz

This results that the cost-reduction factor offered by WDM will reduce due to the decrease of WDM channels sharing the common WDM components. In order to achieve cost-effective LH WDM transmission with high-speed channels over 1 Tbps, it is necessary to expand the optical signal amplification bandwidth large enough for accommodating sufficient number of WDM channels. Various broadband optical amplified transmission experiments have been reported so far as shown in Fig.6 [13-18].

Among them, the optical parametric amplifier using periodically-poled Lithium Niobate (PPLN) can realize a uniform gain and noise figure within the amplification bandwidth at desired wavelength band, and has the advantage of low excess noise in the optical parametric amplification process [19].

Recently, we conducted S+C+L band LH optical amplified WDM transmission experiment using the PPLN -based inline amplifiers with more than three times wider optical bandwidth than that of Erbium-doped fiber amplifier (EDFA) in the using 1-Tbps class channels as shown in Fig.7 [17,18]. The optical parametric wavelength band conversion (WBC) is also promising as a cost-effective means of generating optical signals at the bandwidth other than the C+L band [20]. Recently, ultra-wideband optical signal generation and transmission was tested using low-noise, high-efficiency PPLN based WBC at S band [21] and U band [22]. This wideband WBC is expected as cost-effective realization of signal outside of C+L band in the future ultra-wideband WDM system.

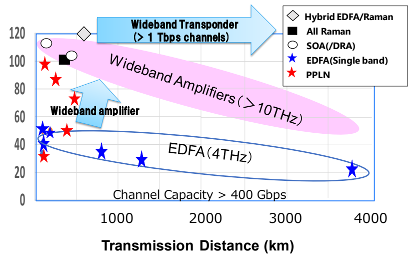

Fig. 6: Optical bandwidth enhancement beyond C+L band for over-Tbps channel based WDM systems.

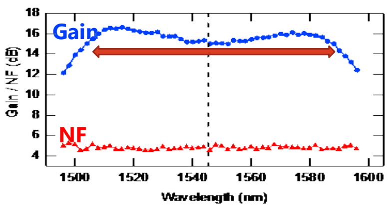

Fig. 7: More-than 2-time optical bandwidth enhancement using PPLN optical parametric amplification repeater

Enhancement of Channel Capacity and Extension of optical signal bandwidth by SDM

SDM is very effective to both channel capacity enhancement and the usable optical signal bandwidth extension. Using a trench-assisted 4-core-fiber transmission line produced by multi venders with the same specification, 118 Tbps inline-amplified transmission over 300 km was demonstrated using typical PDM-16QAM format [23]. A power-efficient and compact multicore optical inline amplifiers were also demonstrated by using a core-pumped multi-core EDFA inline repeater. Recently, several organizations start discussion to develop SDM fiber standard including weakly coupled 4-core fiber with the same cladding diameter as the existing SMF in International Telecommunication Union - Telecommunication Standard Sector [24].

By using the spatial super channel, it is also possible to relax the electrical bandwidth requirement in the future optical transceiver circuit by spatial multiplexing number *m*. Furthermore, it is expected to increase the number of WDM channel by *m* in the limited optical amplification bandwidth as compared with that in SMF-based system.

In the literature [25], an 8-degree SDM ROADM scalable to the node throughput over 1 Pbps was experimentally demonstrated using both 4-core fiber and conventional SMF. Here, spatially-multiplexed super channels with the total channel capacity of 1 Tbps (250 Gbps/core) were used to be tested with PDM-QPSK format and the 1 Tbps super channels are successfully transmitted through the experimental SDM ROADM with the WDM channel count over 100 in virtual 3-node system in the C-band. For the cost-effective realization of the spatial super-channel transceiver, it is necessary to develop integrated packaging of DSP-ASICs and optical frontend circuits such as co-packaged optics based on Silicon photonics platform.

In mode-multiplexed SDM systems, it is possible to increase *m* over 4 by introducing the advanced multiple input and multiple output (MIMO) digital signal processing while keeping sufficient WDM channel number. The novel cyclic mode group permutation scheme was proposed for mode multiplexed inline-amplified system to reduce the accumulation of differential mode delay and mode dependent loss [26]. The proposed scheme realized more than 10-mode multiplexing transmissions over 1000 km [26, 27] (see Fig.8).

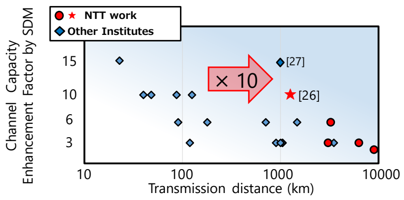

Fig. 8: Over 10-time channel bandwidth enhancement using SDM based on mode multiplexing

Conclusion

Key enabling technologies for realizing future high-capacity transport system with channel rate over Tbps are described. The expansion of both channel bandwidth and optical signal bandwidth by WDM and SDM should be carefully considered for realising future LH transport systems with over 1-Pbps system capacity.

Acknowledgement

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