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A REVIEW ON MULTI-BAND OPTICAL COMMUNICATION SYSTEM

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ABSTRACT

Multiband optical communication has attracted a lot of interest since it is difficult to increase capacity per optical fibre within traditional, constrained bandwidths. Our goal is to increase bandwidth from the currently popular C or L bands to other bands like the S, E, and O bands. Multiband optical communication is the promising technique to extend the lifetime of currently deployed networks. In this paper, we review the components, potentialities and challenges of Multi-band optical communication system over single mode fibers, compared to transmission solutions such as multi-fiber (MF), multi-mode fiber (MMF) and multi-core fiber (MCF).

Keywords: Multi-band, Multi-core, Multi-mode.

INTRODUCTION

The two most crucial factors to take into account when constructing any communication system in the modern world are data rate and bandwidth. One system that can provide a high data rate and bandwidth of the order of Terahertz is optical fiber communication. The demand for bandwidth that optical fiber transports around the world increased significantly as a result of several user-based applications. There are many ways to handle this difficulty

(i) Utilization of high spectral efficiency techniques, better DSP, and stronger FEC.
(ii) Lighting up new, possibly dark, fibers
(iii) Deploy novel multi-core/mode fibers.
(iv) Enabling the usage of the entire low-loss spectrum of single-mode fibers through a multi-band (MB)approach (Ferrari 2019).

From all transmission techniques mentioned in table-1, multiband transmission is a promising technique to fulfill bandwidth requirements, aiming at transmitting over the entire low-loss spectral window of single–mode fiber as shown in fig 1. This will increase the system capacity and thus delay new fiber deployment. Actually, the low-loss transmission bandwidth of optical fiber is much larger than the presently used 5THz of the C-band. The fiber bandwidth that is considerably usable for long distance transmission occupies the wavelength range from 1260 to 1625 nm, where typical fiber loss is as low as 0.35 dB/km. This corresponds to the full channel bandwidth of 53 THz. Multiband transmission exploits this characteristic to increase the transmission capacity. Table 1: List of potentialities and challenges of MBT in terms of pros and cons when compared to transmission solutions such as MF, MMF, andMCF (Napoli 2018)

Table 1

Strategy	**Pros**	**Cons**	**Maturity**	**Capacity**
Multiple SMF	1) Mature technology Exploits already deployed dark SMF	1) Costly new fiber deployment Complex management due to SDM networks	High maturity Already available	Proportional to the number of available SMF
Multi-core/Multi-mode fibers	High capacity per optical fiber	1. The new deployment of optical fibers 2. Development of new components Complex management due to a large number of WDM channels and different cores	Significantly low maturity Unlikely to be ready for deployment in the next few years	Proportional to the number of cores, and modes
Multi-Band transmission	Explore the full low-loss region of SMF Maximize Previous investments	Development of new components for O, E, and S bands Complex management due to a large number of WDM channels	Low maturity Available technology possible to deploy in a few years	Up to 10 times the capacity of current SMFs

Single mode fibers (SMFs) present the minimum attenuation within the C-band which is the fundamental factor for the development of optical communication. The demand for huge bandwidth is required due to an increase in IP traffic, 5G, and high-capacity access networks. One strategy to cope with enormous bandwidth demand is to exploit the remaining low-loss windows that are transmission bands beyond C (Hoshida 2022).

Table 2: Low-loss transmission bands of single-mode fibers

Name	O-Band	E-Band	S-Band	C-Band	L-Band

Wavelength range(nm)	1260-1360	1360-1460	1460-1530	1530-1565	1566-1625
C-band				↔ 35nm	
C+L band				↔ 95nm	
Average fiber loss(dB/km)	0.36	0.28	0.22	0.18	
Multi-band	↔ 365nm				

Figure 1 shows the loss of standard single mode fiber and zero water peak optical fiber as a function of wavelength with a low loss window divided between “original” O- (1260–1360 nm), “extended” E- (1360–1460 nm), “short” S- (1460–1530 nm), “conventional” C- (1530–1565 nm), and “long” L-(1565–1625 nm) bands.

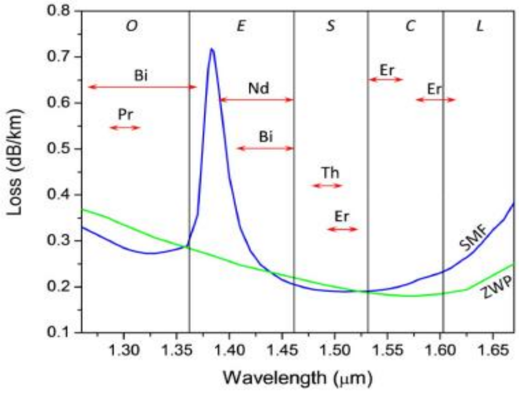

Figure 1. Loss of single-mode fiber and zero water peak as a function of wavelength. Arrows depicts amplification range of doped fiber amplifiers. Bi- bismuth; Er – erbium; Nd –neodymium; Pr- praseodymium; Th – thulium (Mikhailov 2022)

Overall, the fiber has approximately 53 THz low-loss single-mode bandwidth, while only 11 THz is currently amplified by C- and L- band erbium-doped fiber amplifiers (EDFA).

T. Hoshida et al. (2022) have considered the merits and challenges of an Ultra-wideband (UWB) optical transport system beyond conventional bands to meet this expected capacity growth. They have identified technologies and application areas where UWB may have a significant impact. They reviewed the state-of-the-art UWB system demonstrations, their enabling technologies, and unique technical issues to UWB systems, such as system modeling and design, transceiver impairments, and optical amplification technologies. They also looked at a new type of fiber, hollow-core NANF, which might provide future ultra-wide bandwidths with negligible nonlinearity (Mikhailov 2022).

L. Rapp et al. (2022) discussed Challenges and the current level of development of different amplification technologies. Characteristics of different amplifier technologies for signal amplification in different wavelength bands are detailed. In particular, the suitability of these technologies for short–term and mid-term implementation is considered. An important criterion is the availability of qualified components, notably the required pump laser diodes. Presented data indicate that rare–earth doped fiber amplifiers and Raman amplification are suitable candidates for amplification in the S-band, the C–band, and the L–band. Furthermore, it has been shown that the characteristics of ions used for wavelength bands other than the C-band and the L-band are less favorable as compared with erbium. This limits the useable technologies to the two amplification technologies that are already deployed now, namely Erbium-doped fiber amplifiers and Raman amplification. It has been found that Raman amplifiers offer a total bandwidth that is 40% larger than the bandwidth provided by the combined use of C–band and L–band amplifiers (Rapp 2022).

B. Feng et al. (2022) demonstrated that the total capacity of S+C+L band transmission can reach more than times larger than that of only C band transmission when deploying G.654.E fiber with a short span of 60 km without Raman amplification. This should be a cost-effective approach to realize multi-band, large-capacity, and long-haul transmission. We evaluate the performance of 150nm SCL band optical transmission over 1280km G.652.D and G.654.E fibers. S+C+L band transmission without DRA can only achieve a total capacity of 56.7 Tb/s(2.3 times larger than the 24.4 Tb/s of C-band transmission) with three times the bandwidth. When deploying G.654.E fiber with a 60km span length, the total capacity can reach up to 87.1Tb/s (3.6 times) even without DRA. By optimizing power allocation and system configuration, SCL band long-haul transmission enables the same performance as commercial C-band systems (Bofeng 2022).

N. Deng et al. (2022) addressed three of the key technical challenges for multi-band, especially C+L-band systems. They first discussed different optical layer architectures for multi-band systems. Multi-band OA technologies are reviewed and a new approach based on hybrid EDF and BDF OA was proposed, which supported amplification of >100-nm extended C+L spectrum. They further summarized several recent multi-band WSS technologies, and report optical design results of a 2×35 WSS supporting >100-nm spectrum, which can realize optical specifications comparable to conventional C-band WSS. They study SRS-induced power transfer characteristics for the extended C+L system and propose an OSP-OA scheme that can equalize the multi-band WDM channels on a per span basis (Deng 2022).

C. Zhang et al. (2022) studied the optical layer impairments such as the Multipath interference due to LP01-LP11 mode coupling and the SRS and their mitigation in C+L+S+E+O multi-band optical networks based on the next-generation ITU-T G.654-compliant loss-minimized large-effective-area fibers, as well as legacy G.652 fibers. Additional considerations of diverse optical link conditions on amplification schemes, link distances, and cost constraints are made, for provisioning C+L+S+E+O multiband optical networks with the combined use of both G.652 and G.654 fibers, aiming for the optimal utilization of the multi-band transmission in future ultrahigh-capacity optical networks for a wide variety of application (Zhang 2022).

D. Uzunidis et al. (2021) studied an optical multi-band (OMB) link with an amplification scheme based on commercially available rare-earth doped fiber amplifiers for the O, S, C, and L-bands. They derived a closed-form expression for the attainable transparent reach of each band of the link (taking into account the impact of the ASE accumulation and the four-wave mixing (FWM) crosstalk), and then they proceeded to the calculation of the link's capacity and the capacity-length product. The proposed physical layer analysis showed that systems based on currently available components can exceed a capacity of 130 Tb/s for short distances such as 150 km and 40 Tb/s for longer ones, e.g., >2000 km. It also illustrated the fact that there is a tradeoff between the modulation format and the attainable reach (as the higher cardinality modulation formats require a higher optical-to-signal noise interference ratio(OSNIR) to attain the same BER), which resulted in a decreased bit rate times reach product for the higher modulation formats (Uzunidis D. 2021).

A. Donodin et al. (2021) demonstrated transmission of four 10 Gbit/s NRZ channels in the range of 1410-1460 nm over 160 km of SMF-28 fiber with a BDFA. The designed amplifier has a maximum gain of 32 dB, and a minimum NF of 5 dB. The system performance has been examined and compared at different wavelengths and fiber lengths. Their results indicate a high potential of the BDFA for capacity expansion of existing telecom links. The high optical gain and relatively low NF of the BDFA make it an attractive candidate for practical applications, especially in the E-band, where SMF-28 has low optical dispersion (Donodin 2021).

B. Correia et al. (2021) described a launch power control strategy suitable for C+L+S multiband transmission, targeting to optimize the quality of transmission and offered capacity. They showed that, with the adopted strategy, it is possible to maintain or increase the average GSNR and flatness per span in all bands as well as increase the delivered traffic for OLSs with a large number of spans in bands with lower QoT. To reduce the SRS impact on the quality of transmission (QoT), assessed in this work by the generalized signal-to-noise ratio (GSNR) (Rapp 2022), the power launched into the optical fiber needs to be optimized. This can be realized by the multiband power control unit (PCU), part of the software-defined networking (SDN) controller, on a per-band basis, setting each amplifier working point for all-optical line system (OLS) inside an optical network, This control intends to maximize the average GSNR, while still enabling a flat GSNR profile per band (Correia 2021).

X. Gao et al. (2021) proposed a multi-band optical fiber transmission system based on multicarrier and adaptive modulation methods. The adaptive bit allocation in each band is performed in a multi-band system. MBT has different channel characteristics in each band. For example, the C+L-bands have the lowest loss, the O-band has a zero-dispersion point, and so on. These different channel characteristics have different effects on the signal transmission in the channel. They have shown that we can improve the overall transmission efficiency by performing different modulations and power distributions on different bands. The simulation results show that the method can improve the performance better than that of the traditional uniform bit allocation. In addition, we can see the influence of dispersion on signal transmission more clearly through the bit error rate curve (Gao 2021).

D. Uzunidis et al. (2021) developed a rigorous OSNIR optimization method to assess the potential of three connectivity schemes employing the E, S, C, and L bands, Via the subsequent optimal launch powers per band, the optical reach and the corresponding performance trade-offs for these schemes were deduced revealing that a uniform OSNIR performance maximizes the number of available channels, albeit a slightly reduced reach. They considered an OMB system with > 200 nm of bandwidth (1410-1615 nm) exploiting the E, S, C, and L bands. With the introduction of the E-band, it becomes evident that nonlinearities (NLs) and in particular interband effects, such as stimulated Raman scattering (SRS), play an increasingly dominant role in the overall OMB system performance. Connectivity in multi-band networks depends on the attainable optical performance for some system-level parameters like the number of channels, modulation format, and symbol rate

MULTI-BAND OPTICAL COMMUNICATION SYSTEM

International Telecommunications Union-Telecommunication (ITU-T) standardization sector has defined original band (O-band), extended band (E-band), short-wavelength band (S-band), conventional band (C-band), long-wavelength band (L-band), and ultra-long wavelength band (U-band) for optical communication (Rapp 2022). The O-band (1260 nm to 1360 nm) was used in initial optical demonstrations. However, O-band was replaced by E-band (1360 nm to 1460 nm) because of relatively lower attenuation. However, the water absorption peak occurs at around 1380 nm, which is in E-band. The improvement in fiber manufacturing techniques avoids the water peak, but the attenuation remains high. The region between 1460 nm to 1530 nm is termed as the S-band, the attenuation in this region is relatively lower than both the O-band and E-band. Among all the optical bands, the least attenuation was achieved in the C-band with the improvements in the fiber manufacturing process. The C-band quickly became the most obvious choice in practical optical networks, which is because of the least attenuation in the C-band, and due to the availability of well-developed optical amplifiers.

Table 3: Wavelength bands in a multi-band optical communication system

Band	Descriptor	Wavelength (nm)	Frequency (THz)	Bandwidth (THz)	Central Frequency (THz)
O	Original	1260-1360	220.59-238.10	17.25	229.07
E	Extended	1360-1460	205.48-220.59	14.81	212.79
S	Short	1460-1530	196.08-205.48	9.13	200.65
C	Conventional	1530-1565	191.69-196.08	4.13	193.89
L	Long	1565-1625	184.62-191.69	6.96	188.07

Apart from the lowest attenuation, the inventions of the Erbium-doped fiber amplifier (EDFA) and Raman amplifier played an essential role in making C-band the obvious choice over other optical bands. Matured optical amplifier technology of EDFA and Raman amplifier for C-band made long-distance and low-power budget optical networks possible. C-band is only a small portion of the entirely usable optical range, and the use of only the C-band is a resource wastage because C-band is a tiny portion of the broader optical range (Deng 2022).

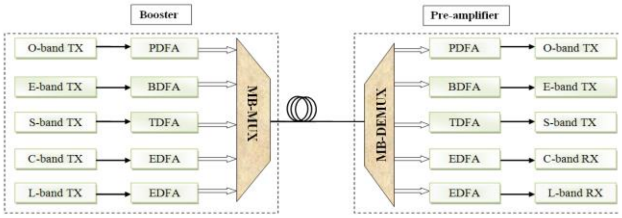

Figure 2. Multi-band optical communication system

Multi-band is a realistic and practical approach to increase the capacity of optical networks as it efficiently uses the available optical fiber infrastructure, thus postponing new fiber rollouts. Multiple fiber transmission is inevitable but Multi-band transmission (MBT) is an effective technology to better exploit the infrastructure by enhancing spectral efficiency. The exploitation of the multi-band optical communication system leads to the transmission of a higher number of channels which increases the overall network capacity. Figure 1 displays a simplified block diagram of a multi-band optical communication system for a point-to-point link such as the ones for data-center interconnection.

MULTI-BAND OPTICAL COMMUNICATION COMPONENTS

The low loss of G.652D fiber across all bands i.e. 1260 nm -1626 nm could be exploited to increase the transmission bandwidth by several tens of THz. For metro and regional distances, where fiber losses (even in the o-band) should be minimal, would be fiercely competitive against MF, MC, and MM. To utilize the whole fiber bandwidth covering low-loss windows for communication, multiband optical communication is a promising technique. Multi-band optical transmission promises to extend the lifetime of currently deployed networks. Multi-band transmission aims at exploiting the low-loss spectral windows of single-mode fibers for data transport. Figure 2 displays a key component of a multi-band optical system. Multi-band consists of the following elements:(1) transceiver (laser, modulator,) must be realized possibly with the capability of being tunable over the entire spectrum. (2)the amplifier and filters must be designed by utilizing the best doped material for each band.

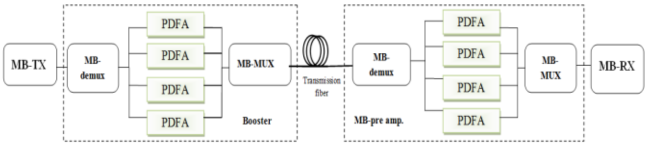

Figure 3: Key components of the Multi-band optical communication system (Napoli 2018).

MULTIBAND CHALLENGES

The main challenge for Multi-band optical communication system is the low maturity of the key components while C-band devices have achieved high maturity. Multi-band optical communication system also has to cope with wavelength-dependent channel characteristics that are the dispersion coefficient D(λ) ranges from –5 ps/nm/km to ≥20 ps/nm/km (from O→L-band) and the fiber loss α(λ) ranges from ∼0.38 dB/km (in O-band) to ∼0.18 dB/km (in C- band). Consequently, to achieve full optimization of transmission over such a wide spectrum, adaptation to the fiber characteristics on a per-channel and per-band basis is required. SRS is also a main issue in the context of multi-band optical communication

CONCLUSION

In this paper, we discussed the great potential and challenges of Multi-band optical communication system. The need for opening SMF transmission beyond C-band is also compared against spatial division multiplexing. At last, we concluded that multiband optical communication is a valid option to deliver the capacity requested by different applications.

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