Remote Pumping in Point to Multi-point Networks

Petr Munster, *Member, IEEE*, Tomas Horvath *Member, IEEE*, Petr Dejdar, *Student Member, IEEE*, and Edvin Skaljo *Member, IEEE*

***Abstract*—A remotely pumped Erbium-doped system for the amplification of an optical signal for long-reach (LR) next-generation passive optical networks (NG-PONs) is presented in this paper. The next-generation networks will be deployed with/over the current point to multi-point technology with/without backward compatibility. Remote pumping allows extending the reach of the optical distribution networks and the magnification of the splitting ratio as well, which is most important for increasing the number of end users in the PON network. In our laboratory, we have successfully verified the functionality of the unidirectional and bidirectional remote pumping system based on an Erbium-doped fiber inserted into the route and remote pumping from a central office. Our measurement results prove that it is possible to extend the total reaching point to the multi-point system without the difficult incidence in the optical distribution network. Based on the results, the proposed amplifying passive optical network approach is capable of being used in passive optical networks in C band for extending the total reach of system or increasing the split ratio.**

***Index Terms*—Amplifiers, Erbium-doped fiber amplifier, Fiber optics, Optical fiber communication, Optical fiber networks, Optical pumping.**

I. Introduction

Over the last several years, the growth of internet traffic has led to building optical access networks (OANs) in many countries [1] - [4]. Optical fibers spread from the area of wide area networks (WANs) to the area of optical access networks and internet service providers (ISPs) are gradually replacing existing copper wiring asymmetric digital subscriber lines (ADSL) and very-high speed digital subscriber lines (VDSL) because of their physical limitations [5]-[7]. Passive optical networks seem to be the most appropriate solution for future access networks due to their advantages. The most limiting factor of these networks is the insertion loss of an optical splitter, which limits maximal achievable distance and a number of end users as well. A remote pumping system can offer an appropriate solution against using a standard Erbium-doped fiber amplifier (EDFA) because it maintains the basic idea of passive optical networks (PONs): a passive distribution network without any active elements.

Conventional passive optical networks have been used for many years since 1998, when the passive optical network asynchronous transfer mode passive optical network (APON) was standardized according to the International Telecommunication Union (ITU-T) but the first PON was proposed by British Telecom in 1987 [8]. The development of passive optical network standards continued with broadband PON (BPON) [9], gigabit PON (GPON), and next-generation PON (NG-PON) [10]-[12]. The rival standardization union Institute of Electrical and Electronics Engineers (IEEE) also developed a passive optical network in 2004, when the Ethernet PON (EPON) passive optical network, which was to be a direct competitor against GPON networks, was standardized [13]. These two types of optical access networks are now the most widely used. On the other hand, the deployment strongly depends on country terrain and number of households [14]-[16]. The newest standard of IEEE is 10GEPON and that of ITU-T is XG-PON, which allows 10 Gbit/s transmission and greater splitting ratios (up to 1:128, previously only 1:64) compared with previous generations [17]. In recent years, the next generation of passive optical networks began to be developed.

We can divide NG-PON standards into two groups: NG-PON1 and next-generation passive optical network stage 2 (NG-PON2). While NG-PON1 preserves the existing optical distribution network (ODN), the second group, NG-PON2, allows changes of ODN. Representative of the first category is XG-PON, which is specified in ITU-T G.987 [18]. The maximum bit rate was set to 10 Gbit/s in the downstream direction and 2.5 Gbit/s in the upstream direction. This technology is based on time division multiplexing (TDM) [18].

NG-PON2 is primarily based on hybrid time and wavelength division multiplexing (TWDM). This standard is specified in G.989.1 [19]. After selecting a technology, the second most important step was to select a wavelength. The first idea was to use free wavelengths of the XG-PON standard. Over time, assorted utilized wavelengths were within a free range between 1596 to 1603 nm for the downstream direction, and from 1524 to 1544 nm for the upstream direction. On the other hand, this standard supported a 160 Gbit/s bit rate via 16 pairs of wavelengths. Only 40 Gbit/s topology without remote pumping was measured [20], [21] in the laboratory.

The amplification of optical signals is a necessity for transport, metropolitan and, sometimes, access networks. Raman amplifiers, EDFA or semiconductor optical amplifiers (SOA) could be used, depending on the network type. All of them

Manuscript received December 8, 2021; revised January 25, 2022. Date of publication February 25, 2022. Date of current version February 25, 2022. The associate editor prof. Ivan Radoš has been coordinating the review of this manuscript and approved it for publication.

The research described in this paper was financed by a grant from the Ministry of the Interior of the Czech Republic, Program of Security Research, VI20192022135, for "Deep hardware detection of network traffic of next generation passive optical network in critical infrastructures".

Petr Munster, Tomas Horvath, and Petr Dejdar are with the Department of Telecommunication, Brno University of Technology, Technicka 12, 616 00 Brno, Czech Republic, e-mails: [munster, horvath, dejdar]@vut.cz.

Edvin Skaljo is with the Department of Physics, University of Sarajevo Faculty of Science, Sarajevo, Bosnia and Herzegovina, e-mail: skaljo@ieee.org.

Digital Object Identifier (DOI): 10.24138/jcomss-2021-0188

require a power supply to function. The problem occurs if we need to amplify an optical signal in the remote node without electricity. The best solution for this specific application is to deploy remote pumping amplification. A similar situation could occur in PON, where the loss of optical splitters and distribution network is the biggest limit.

Optical in-line amplifiers optically powered via the transmission fiber are a promising technology for increasing the distance between electrically powered equipment in optical transmission systems. Repeaters are an effective way to increase the span length, but they require electrical power and associated performance monitoring, which significantly adds to installation and maintenance costs [22].

Unrepeated systems based on remote amplification, however, may become less-expensive alternatives to repeated systems. Remotely pumped amplifiers are particularly attractive for submarine systems, in which repeaters pose special challenges and significantly add to the cost. Optical power levels in the range of 100 mW and above are available from semiconductor-based pump sources, making remote pumping a realistic option. Remote pumping is also very useful in PON; thanks to this, amplification is possible to extend the maximum split ratio or distance between the optical line terminal (OLT) and optical network unit (ONU) [23].

The rest of this paper is structured as follows. Section II addresses our measurement setup. Section III discusses our measurement results. Finally, Section IV concludes our paper.

A. Original Contribution

The main contribution of this paper is to prove that remote pumping in passive optical networks is possible without active elements in optical distribution network. Our measurement setups were divided into unidirectional and bidirectional data transmission. We also focused on experimental verification of unidirectional and bidirectional pumping of Er fiber. The paper mainly focuses on high-speed passive optical networks such as next-generation passive optical network (stage-2) because of the used pump wavelength at 1480 nm. Based on well-known technique (remote pumping) and measurement results, the total split ratio of the optical distribution network can be extended without the need to use active elements in the optical distribution network. Remote pumping systems offer excellent potential for future applications in passive optical networks.

II. Remote Pumping

There are two main limitations of passive optical networks: the attenuation of passive optical elements, especially optical fibers/splitters and total distance between OLT and ONU [23]. The total attenuation of the distribution network is the main limiting factor for the maximum distance between OLT and ONUs, as well as for the maximum splitting ratio, which determines the number of end users. To eliminate this, it is possible to use, e.g., a Raman amplifier on the OLT side of the network. The advantage is that there is no special fiber required, similar to in EDFA. On the other hand, Raman amplifiers are quite expensive and have lower gain and optical signal-to-noise ratio (OSNR) in comparison with EDFA [24]. Furthermore, the disadvantage of Raman amplifiers is also that the entire network must be made without optical connectors, since each connector would cause optical reflections that would increase the optical noise and decrease the signal-to-noise ratio in the network. EDFAs are the most widely used optical amplifiers, but due to the necessity of bidirectional amplification in the route, and hence power supply use, they are not suitable for PONs [23]. Selecting a suitable signal amplification principle is very important and can influence signal Q-factor or bit error rate (BER) [25]. Erbium-doped fiber amplifiers are mostly used in telecommunication because of their amplifying properties. Moreover, in general there are only two most important elements – laser pump diode and Erbium-doped fiber, which reduce cost and complexity of the system. Many experiments using EDFAs in passive optical networks where published. Mainly are focused on the measurement of signal amplification parameters. These works, however, do not consider remote amplification and need active power supply in ODN hence these types of networks are not fully passive yet [26] [28]. There are also some experiments describing the specific application of Erbium-doped fiber (EDF) and laser pump diodes. For example, in [29] authors describe unidirectional signal transmission with an active EDFA. They used the Raman pump for pumping EDF through the optical coupler. In this experiment, the influence of EDF length on signal amplification was evaluated. Subsequently, the possibility of using EDFA at the beginning of the passive optical network PON is discussed. Another experiment describing remote pumping by adding EDF before the distribution fiber can also be find in [30]. Special systems for amplification the signal in C- and L-band for use in a bidirectional system using two Erbium-doped fibers, circulators, and a pump reflector are described in [31], [32]. Another research focus on use of active bidirectional EDFAs within a passive optical networks [33]. Although all papers above describe signal amplification in PONs, mostly it is not fully passive infrastructure because of need to active element in the ODN.

Remote pumping is the solution for the optical signal amplification with respect to the main idea of maintaining a completely passive optical network. The principle is that the pump laser diode source is a part of the OLT unit in the central office, and the pump signal transmission uses the same optical fiber as the data signal to reach the place where the Erbium-doped fiber is situated. The ideal solution may be an amplifying passive optical splitter (APOS) using an EDF as a part of the optical splitter. Figure 1 shows the scheme of a simple APOS. The extended version of APOS should also include a WDM filter, which would filter out the remaining 1490 nm signal power, in order to avoid possible degradation of the OSNR of useful signal on the photodetector of the ONU unit. However, due to relatively high insertion loss of passive optical splitter (especially for higher splitting ratios), the pump signal is sufficiently attenuated and the WDM filter does not need to be used. To ensure sufficient power required to pump the Erbium-doped fiber, it is preferable to use a pump diode with a wavelength of 1480–1490 nm. Although 980 nm wavelength pumps are more common in today EDFA because of lower noise and higher gain, the attenuation of the signal at 980 nm is more than 1.5 dB/km, which causes approx 15 dB signal attenuation in a 10 km long single-mode optical fiber and hence higher pump power would be needed for remote pumping.

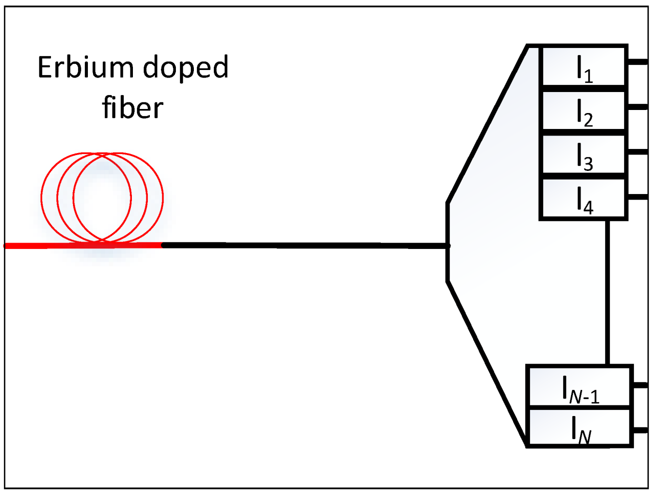

Fig. 1. Scheme of proposed amplifying passive optical splitter (APOS).

In [23], some basic systems of remote pumping were proposed. The RP for signal amplification in many types of passive optical networks is used there. For example, in [34], a remotely pumped hybrid TDM/WDM PON network with 256-splitting ratio and 80 Gbit/s bit rate was proposed. The authors used a reconfigurable semiconductor optical amplifier (RSOA) for direct modulation to achieve high-speed bit rate. In [35], the authors described a remotely reconfigurable remote node for hybrid ring-tree passive optical networks where the carrier signal was amplified by remote pumping. A remotely dual-pumped system for long-reach PONs and flexible deployment was proposed by Schrenk et al. in [36]. The authors described flexible wavelength division multiplexing and time division multiplexing network architecture for a converged metro-access environment using remote pumping.

Our system was proposed with respect to low-price development. We have proposed a bidirectional system for remote amplification of an optical signal in the range of wavelengths from 1530 to 1560 nm using a pump laser diode with central wavelength of 1490 nm and 4 m of an Erbium-doped fiber situated in the ODN. This system is fully transparent to any technology employing the wavelength range.

A. Remote Pumping Measurement Setup

We have performed experimental measurement for remote pumping verification in three setups, which are shown in Figure 2, 4, and 5. The first measurement is a simple setup based on unidirectional remote pumping for unidirectional signal transmission. The advantage of this setup is its simple configuration a fully control amplification thanks to unidirectional signal transmission of useful signal. The second setup is for bidirectional useful signal transmission using WDM technology. In this setup both direction (downstream, upstream) are amplified simultaneously. The third measurement is almost the same as the second setup, but without the 20 km of fiber optic route.

B. Unidirectional Transmission Measurement Setup

This measurement setup was created for the demonstration of the remote pumping principle for the unidirectional transmission systems. This system could be used, for example, in PON networks, where the ONU units typically have smaller output power in comparison with the OLT unit. This unidirectional amplification could thus be extended to the maximal reach of the optical distribution network. The scheme is shown in Figure 2 and photo of the real setup in Figure 3.

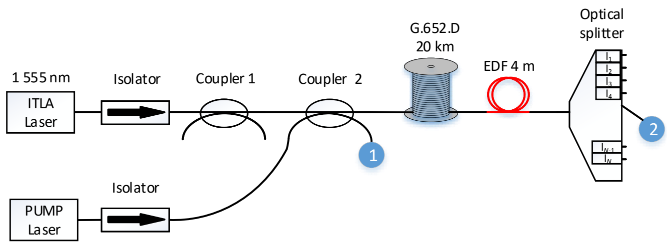

Fig. 2. Experimental setup for unidirectional transmission.

A useful optical signal from the tunable distributed feedback (DFB) laser (integrable tunable laser assembly, tuned to ≈1555 nm) goes through an optical isolator to the first coupler (2:2), which is used for the power level measurement, and then goes through the second coupler to the optical fiber spool with 20 km of G.652.D optical fiber. Behind this spool, 4 meters of Erbium-doped fiber is connected. The splitter is connected at the end of the optical distribution network. The splitting ratio was set to 1:4, 1:16 and 1:256 for comparison of measurement results. The optical signal from the 1490 nm pump laser goes through the second optical isolator to the second coupler, where it is mixed with the useful optical signal from the integrable tunable laser assembly (ITLA) laser. At the end of the distribution network (before the splitter), the useful signal is amplified due to the Erbium fiber, which is connected there for the effect of remote pumping. The optical spectral analyzer (OSA) was used for power level monitoring at the first, respective second measurement point.

C. Bidirectional Transmission Measurement Setup

The remote pumping system for bidirectional amplification of the optical link was realized in this part. Bidirectional amplification is necessary in most types of passive optical networks if extending the maximum length of the ODN or splitting ratio is desired. Remote pumping could be a very useful type of optical amplification without any active elements in the distribution network. The scheme of this setup is shown in Figure 4.

The basic principle is similar to the unidirectional setup. The main difference lies in the number of lasers. In this setup, we have used two DFB lasers and one pump laser. This measurement was only acquired with the 1:256 splitter. The

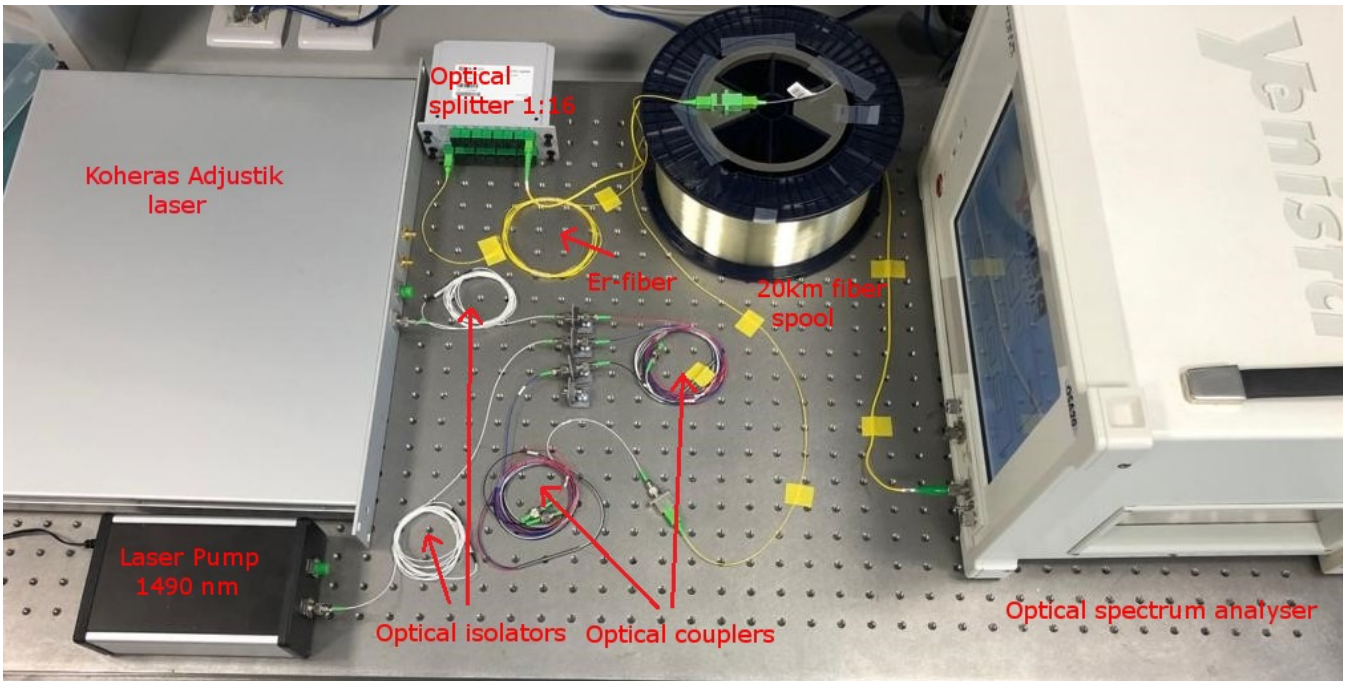

Fig. 3. Photo of the real experimental setup for unidirectional transmission.

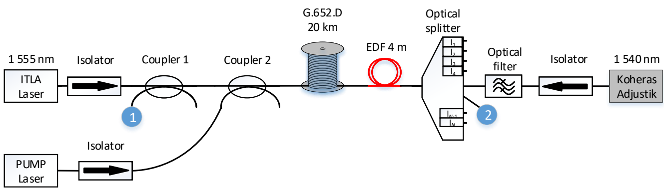

Fig. 4. Experimental setup for bidirectional transmission.

split ratio of 1:256 is the maximum value considered for NG-PON2 standards.

The useful optical signal from the tunable DFB laser (ITLA laser, tuned to ≈1555 nm) goes through the optical isolator to the first coupler (2:2), which is used for power level measurement, and then goes through coupler 2 (2:2) to the optical fiber spool with 20 km of G.652.D optical fiber. Behind this spool, the splitter with splitting ratio of 1:256 is connected. Remote amplification is quite complicated in this setup. Amplification in downstream (A → B) and upstream (B → A) directions is realized by one pump laser. In the downstream direction, the signal from the pump laser goes through the optical isolator and second coupler to the 20 km fiber spool and 4 m of Erbium-doped fiber. This is the point where the useful optical signal is remotely amplified in the downstream direction. Additionally, in the upstream direction, the useful optical signal is also amplified at this point of the optical link. This signal from the second DFB laser, Koheras Adjustik (ADJ laser, tuned to 1540 nm), goes through the optical isolator and bandpass filter to coupler to optical splitter 1:256. Measurement point 1 and 2 in the scheme are used for monitoring of the power levels by OSA.

D. Bidirectional Transmission with Bidirectional Pumping Measurement without Fiber Optic Spool

This setup is very similar to a previous scheme, as shown in Figure 5. The main difference is that the Erbium-doped fiber is situated directly within the optical distribution network. This measurement was performed for purposes of studying system behavior.

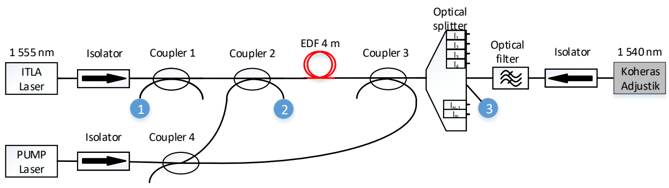

Fig. 5. Experimental setup for bidirectional transmission without fiber optic route.

The useful optical signal from the tunable DFB laser (ITLA laser, tuned to ≈1555 nm) goes through the optical isolator to the first coupler (2:2), and then goes through coupler 2 (2:2) to the Erbium-doped fiber, coupler 3 (2:2) and a splitter with splitting ratio of 1:256. Remote amplification is realized by one pump laser as well but signal is coupled to Erbium-doped fiber from both sides. In the downstream direction, the signal from the pump laser goes through the optical isolator and coupler 4 (2:2) to coupler 2 and 4 m of an Erbium-doped fiber. This is the point where the useful optical signal is remotely amplified in the downstream direction. Additionally, in the upstream direction, the useful optical signal is amplified at this point of the optical link. This signal from the second DFB laser, Koheras Adjustik (ADJ laser, tuned to 1540 nm), goes through the optical isolator and bandpass filter to the ODN.

System of remote pumping could be used for WDM-PON networks due to the wavelengths of useful signals and the pump. This system works in the C band. System was proposed in consideration of low-price development. We proposed the bidirectional system for remote amplification of an optical signal within the range of wavelengths between 1530 and 1560 nm using the pump laser diode with wavelength of 1490 nm and an Erbium-doped fiber situated in the ODN. Moreover, system is transparent for any technologies using these wavelengths.

III. Measurement Results and Analysis

Power levels for all measurement setups were measured by an optical spectral analyzer, and the results were compared for measuring with or without the Er-fiber for bidirectional setups in both directions: upstream and downstream. The power of the pump laser diode was set to the maximum value of 160 mW. The output power of DFB lasers was set to the optional value to reach the saturation mode of EDFA amplification.

A. *Unidirectional Transmission Measurement Results*

The results of this measurement are shown in Table I. The results for different splitting ratios may be observed there: 1:4 (see Figure 6), 1:16, and 1:256 (see Figure 7). For all splitting ratios, we can clearly compare values of the output power level with and without the applied Er-fiber. These values were measured at the output ports of the splitters.

TABLE I
Measurements with various splitter types.

Splitter	Laser type	Direction	Erbium fiber	Power level [dBm]
1:4	ITLA	DW	NO	–28.34
1:4	ITLA	DW	YES	–15.84
1:16	ITLA	DW	NO	–28.47
1:16	ITLA	DW	YES	–22.61
1:256	ITLA	DW	NO	–36.71
1:256	ITLA	DW	YES	–27.41

For the 1:4 splitter, the output power was only –28.34 dBm (see TableI) without remote amplification. This value is at the sensitivity limit for most ONUs, and problems with BER could occur [37]. When we have applied remote pumping, the output power increases to –15.84 dBm. The gain was 12.5 dB. The spectral characteristic is shown in Figure 6. The black line is adequate for measurements without Er-fiber. As we can see there, the pump diode was still switched on. In comparison with the red line, which is adequate for measurement with the Er-fiber, we can see that the energy of the pump diode migrates to a useful signal after Er-fiber application and that OSNR remained approximately the same as before.

For the split ratio of 1:256, the situation was very similar (see Figure 7): after Er-fiber application, the power level increases from –28.47 dBm to –22.61 dBm, and so the gain was 5.86 dB.

For the 1:256 splitter (the maximum splitting ratio for NG-PON2 [37]), the output power was –36.71 dBm without Er-fiber and –27.41 dBm with the fiber. The gain of remote amplification was thus 9.3 dB (see Table I).

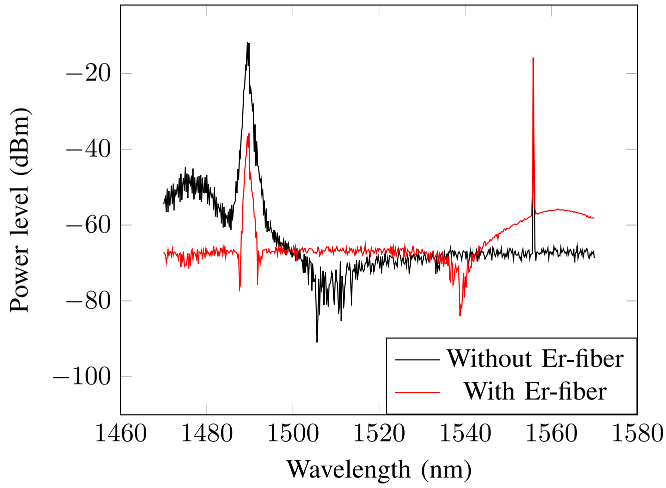

Fig. 6. Optical spectrum for unidirectional transmission with 1:4 splitting ratio, measured at point 2 in Figure 2.

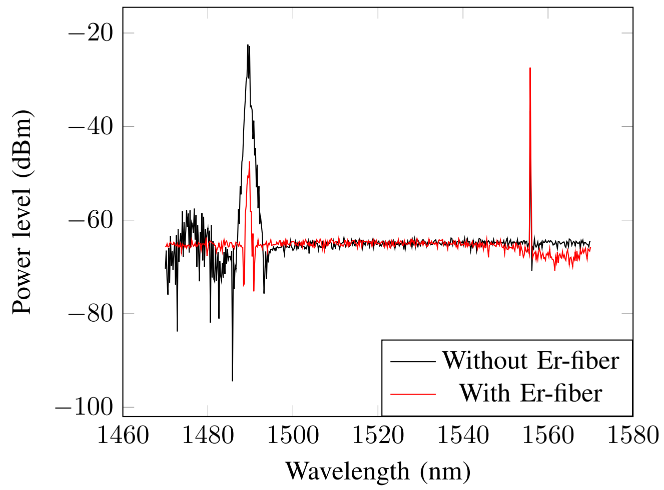

Fig. 7. Optical spectrum for unidirectional signal transmission with 1:256 splitting ratio, measured at point 2 in Figure 2.

B. *Bidirectional Transmission Measurement Results*

This measurement was performed only for the 1:256 splitter. Attenuation of the optical distribution network was high due to the 20 km optical fiber and the splitter with a high splitting ratio. As was mentioned before, two DFB lasers were used. The results are shown in Table II. For the downstream direction, a tunable laser (ITLA) was used. We can compare the difference between power level values: without Er-fiber, the power was only –36.8 dBm; with Er-fiber, the power was –23.41 dBm. The total gain was 13.39 dB. Spectral characteristics are shown in Figure 8. After amplification, OSNR increases again (red line). The optical signal was measured at the splitter's output port.

For the upstream direction, the second DFB laser (ADJ) was used. The power level without remote amplification was –35.93 dBm, and it was –32.9 dBm with remote amplification. The gain in this case was only 3 dB. OSNR was also very low, as exhibited by the pattern in Figure 9. In this graphical

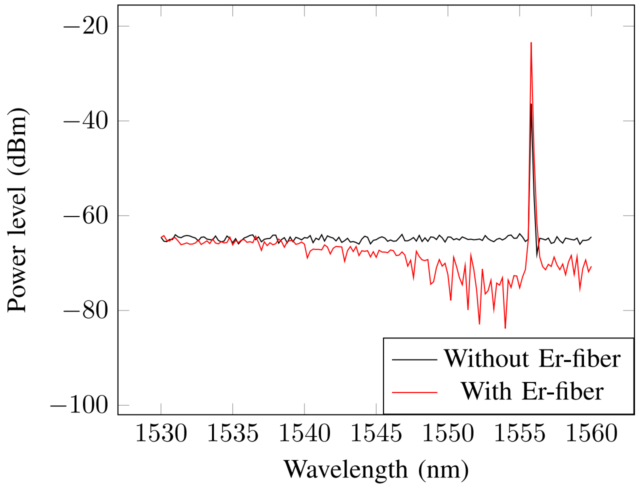

Fig. 8. Optical spectrum for bidirectional transmission measurement: downstream, measured at point 2 in Figure 4.

TABLE II
BIDIRECTIONAL TRANSMISSION MEASUREMENT FOR 1:256 SPLIT RATIO WITH DISTRIBUTION NETWORK.

Splitter	Laser type	Direction	Erbium fiber	Power level [dBm]
1:256	ITLA	DW	NO	–36.8
1:256	ITLA	DW	YES	–23.41
1:256	ADJ	UP	NO	–35.93
1:256	ADJ	UP	YES	–32.9

output of OSA, we can see 2 peaks: the left peak is attributed to the ADJ laser (upstream) and the right peak is attributed to the ITLA laser (downstream). These signals were measured at coupler 1 (see Figure 4). Very low OSNR was caused due to amplifier spontaneous emission (ASE). The reason for ASE generation is a very low-power input signal [38]. Although the OSNR is high and the gain is only 3 dB, the results are still better than those without remote amplification.

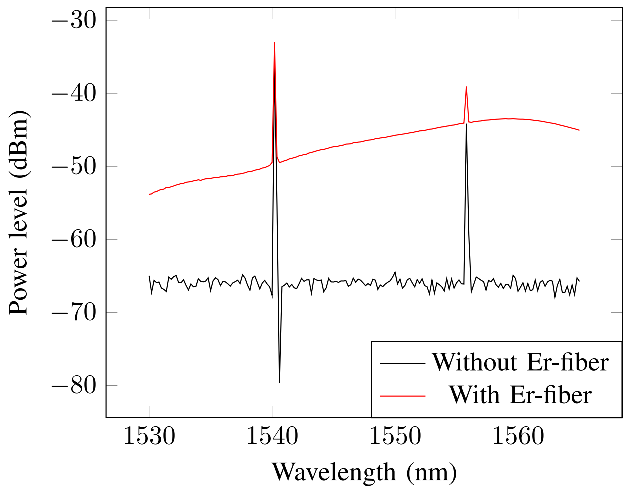

Fig. 9. Optical spectrum for bidirectional transmission measurement: upstream, measured at point 1 in Figure 4.

C. Results of Bidirectional Transmission with Bidirectional Pumping Measurement without Fiber Optic Route

The measurement was very similar to the previous one: the main difference is that no fiber optic spool was used in that case. The reason for this is the low power of the pump laser for this setup. This is the reason why we performed this measurement without optical fibers for demonstration of this principle.

TABLE III
BIDIRECTIONAL TRANSMISSION WITH BIDIRECTIONAL PUMPING MEASUREMENT ON 1:256 SPLIT RATIO WITHOUT OPTICAL SPOOL.

Splitter	Laser type	Direction	Erbium fiber	Power level [dBm]
1:256	ITLA	DW	NO	–42.87
1:256	ITLA	DW	YES	–21.87
1:256	ADJ	UP	NO	–42.56
1:256	ADJ	UP	YES	–31.4

In the downstream direction (ITLA laser), the power on the splitter output was only –42.87 dB (see Table III). If we applied the Er-fiber to the ODN (see Figure 5), the power increases to –21.87 dB and the gain was 20.93 dB. In the graphical output of this measurement (shown in Figure 10), we can see that OSNR was also very high: more than 40 dB. It is a fact that with this system it is possible to amplify very low-power input signals, and then to use a common PIN photodiode instead of an expensive avalanche photodiode (APD) for detection. We have achieved the best results with this measurement setup.

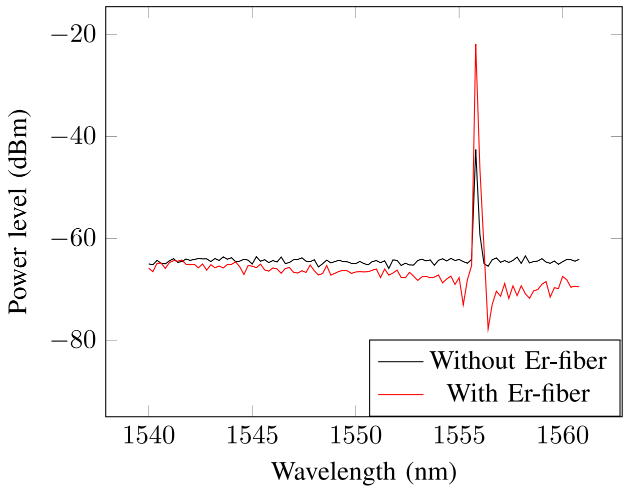

Fig. 10. Optical spectrum for bidirectional transmission with bidirectional pumping with a 1:256 optical splitter, measured at point 3 in Figure 5.

In the upstream direction (ADJ laser), the power measured on coupler 1 (see Figure 5) was only –42.56 dBm. After we applied Er-fiber, the power level increased to –31.4 dB. This result is shown in Figure 11. We can see there that OSNR is over 10 dB, and the gain is 11.16 dB.

In the case of PON connections in the unidirectional mode (only downstream), it has been proven that remote pumping can increase the total reach or split ratio in PON. Specifically, this is an increase of at least 5.86 dB for a 1:16 splitter, as

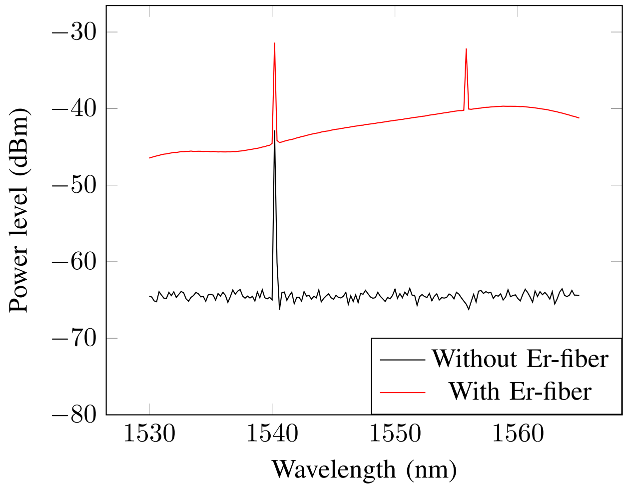

Fig. 11. Optical spectrum showing upstream and downstream signals for bidirectional transmission with bidirectional pumping with a 1:256 optical splitter.

seen in Table I. For the bidirectional PON connection with a fiber spool downstream, the performance values with an Er fiber are 13.39 dB higher than those without an Er fiber, and the power upstream is 3.03 dB higher. The authors [23] obtained better results with double Er-fibers in ODN and double pumping. Note that our measurements relied on single Er-fiber with a length of 4 m in comparison with 15 m in [23]. The article [28] presented a simulation scheme for a WDM-PON 70 km length optical path and a 1:32 split ratio. The simulation scheme allows us to extend the total reach up to 100 km (30 km improvement), which represents 6 dB of attenuation. Note that that distance is not very common in NG-PON2 due to the limitation of timing between OLT and ONU. The article [31] presented that the average gains are 10.55 dB for the C-band EDFA and 10.17 dB for the L-band EDFA. The work [39] demonstrated Raman amplification in a 10G Ethernet-based PON. The total reach between the OLT and ONU was obtained as 40 km. The authors [40] reached 768 customers on a single strand within the WDM Super-PON. The system combines GPON lambda and 8 point-to-point dedicated connections, each with a 10 Gbit/s bandwidth. Notably, the Super-PON defines up to 50 km between OLT and ONU [41]. The Er-fiber can be inserted in a splitter box and/or on an input port in the downstream direction. The Internet service provider administered the central office, which means that there is no additional cost for amplifier installation. These results show an increase in the performance of the PON without the need to intervene in the structures of already implemented PONs. This can be achieved by combining the remote pumping technique with PON. This article, therefore, offers an opportunity to increase the range of PON using remote pumping, as evidenced by many measurements. Remote pumping is a well-known technique in long-haul networks, and we adapted the technique into a passive optical network to extend the reach or increase the split ratio. Based on the results, the increasing split ratio is the main purpose because a synchronization issue can arise between OLT and ONU units with increasing fiber length.

IV. Conclusion

A contemporary trend is to use existing installed transmission media with maximum bandwidth. The same situation exists with optical fibers, especially with optical distribution networks in metropolitan area network (MAN) or local area network (LAN) networks. Rather than active optical networks, the passive optical networks are used for data connectivity as the best method of optical access networks. The limiting factor for PONs is the total attenuation caused due to fiber attenuation, and especially the very high attenuation of the passive splitters. If we want to use the existing distribution network and increase the number of end users or extend the length of the optical route, remote pumping is the best solution because it completely preserves the passive character of the distribution network.

In this paper, we verified the principle of remote pumping technology using Erbium-doped fiber and a laser pump diode for the 1490 nm wavelength. We have designed 3 measurement setups: unidirectional, bidirectional and bidirectional without optical route. From the results described, it is evident that the best results were achieved in bidirectional measurement without the optical route for the downstream direction. The gain was almost 21 dB, the OSNR was over 40 dB and the optical signal was amplified from –42.87 dB to –21.87 dB. If we compare all results, it is obvious that gain and OSNR are higher in the downstream direction. This was caused by the Er-fiber position in topology and by the power levels of both lasers. The best results were achieved if the parameters were optimally set and EDFA was approaching the saturation effect.

We have proposed a bidirectional remote pumping system for passive optical networks, especially for WDM-PON networks, which can function in the C band. We have also designed an amplifying passive optical splitter: the splitter and the pump diode represent the main components of the remote pumping system. Remote pumping systems offer excellent potential for future applications in passive optical networks.

The future work will be a measurement in our next-generation passive optical network with BER/frame error rate (FER) parameters evaluation. Furthermore, an increasing split ratio with the proposed APOS will be tested.

References

[1] G. S. Ford, "Is faster better? quantifying the relationship between broadband speed and economic growth," *Telecommunications Policy*, vol. 42, no. 9, pp. 766–777, 2018. [Online]. DOI: 10.1016/j.telpol.2018.05.006

[2] J. A. Hernandez, R. Sanchez, I. Martin, and D. Larrabeiti, "Meeting the traffic requirements of residential users in the next decade with current ftth standards," *IEEE Communications Magazine*, vol. 57, no. 6, pp. 120–125, 2019. [Online]. DOI: 10.1109/MCOM.2018.1800173

[3] A. Oredegbe and Y. Zhang, "Telecommunications industry efficiency," *Telecommunications Policy*, vol. 44, no. 5, pp. 1–11, 2020. [Online]. DOI: 10.1016/j.telpol.2020.101958

[4] B. Batagelj, V. Janyani, and S. Tomazic, "Research challenges in optical communications towards 2020 and beyond," *Informacije MIDEM - Journal of Microelectronics, Electronic Components and Materials*, vol. 44, pp. 177 – 184, 09 2014.

[5] B. J. Lobo, M. R. Alam, and B. E. Whitacre, "Broadband speed and unemployment rates," *Telecommunications Policy*, vol. 44, no. 1, pp. 1–15, 2020. [Online]. DOI: 10.1016/j.telpol.2019.101829

[6] N. Ioannou, D. Katsianis, and D. Varoutas, "Comparative techno-economic evaluation of lte fixed wireless access, fttdp g.fast and fttc vdsl network deployment for providing 30 mbps broadband services in rural areas," *Telecommunications Policy*, vol. 44, no. 3, pp. 1–19, 2020. [Online]. DOI: 10.1016/j.telpol.2019.101875

[7] D. P. Reed, "Examining the prospects for gigabit broadband," *Telecommunications Policy*, vol. 44, no. 5, pp. 1–15, 2020. [Online]. DOI: 10.1016/j.telpol.2020.101957

[8] J. Stern, J. Ballance, D. Faulkner, S. Hornung, D. Payne, and K. Oakley, "Passive optical local networks for telephony applications and beyond," *Electronics Letters*, vol. 23, no. 24, pp. 1255–1256, 1987. [Online]. DOI: 10.1049/el:19870872

[9] M. Filka, *Optoelectronics for telecommunications and informatics*, 1st ed., Dallas, USA, 2009.

[10] "G.984.1 : Gigabit-capable passive optical networks (gpon): General characteristics," Switzerland, 2008. [Online]. Available: http://www.itu.int/rec/T-REC-G.984.1-200803-I

[11] P. P. Iannone, A. H. Gnauck, D. T. van Veen, and V. E. Houtsma, "Increasing tdm rates for access systems beyond ng-pon2," *Journal of Lightwave Technology*, vol. 34, no. 6, pp. 1545–1550, 2016. [Online]. Available: http://ieeexplore.ieee.org/document/7395266/

[12] P. Chanclou, A. Cui, F. Geilhardt, H. Nakamura, and D. Nesset, "Network operator requirements for the next generation of optical access networks," *IEEE Network*, vol. 26, no. 2, pp. 8–14, 2012. [Online]. DOI: 10.1109/MNET.2012.6172269

[13] "10gb/s ethernet passive optical network," USA, 2009. [Online]. Available: http://www.ieee802.org/3/av/

[14] B. Batagelj, "Deployment of fiber-to-the-home in the slovenian telecommunications market," *Fiber & Integrated Optics*, vol. 32, pp. 1–11, 02 2013. [Online]. DOI: 10.1080/01468030.2012.760686

[15] J. Ratkoceri and B. Batagelj, "Deployment of fiber-based access in the kosovan telecommunications market," *Fiber and Integrated Optics*, vol. 39, no. 2, pp. 53–69, 2020-03-03. [Online]. DOI: 10.1080/01468030.2020.1756541

[16] S. Garg, M. Aggarwal, and A. Dixit, "Power, cost and reach based evaluation of next generation passive optical networks architectures," in *2018 IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS)*. Indore, India: IEEE, 2018, pp. 1–6. [Online]. DOI: 10.1109/ANTS.2018.8710127

[17] C. Bock, J. Prat, and S. Walker, "Hybrid wdm/tdm pon using the awg fsr and featuring centralized light generation and dynamic bandwidth allocation," *Journal of Lightwave Technology*, vol. 23, no. 12, pp. 3981–3988, 2005. [Online]. DOI: 10.1109/JLT.2005.853138

[18] "G.987.1 : 10-gigabit-capable passive optical networks (xg-pon): General requirements," Switzerland, 2016. [Online]. Available: https://www.itu.int/rec/T-REC-G.987.1-201603-I/en

[19] "G.989.1 : 40-gigabit-capable passive optical networks (ng-pon2): General requirements," Switzerland, 2013. [Online]. Available: https://www.itu.int/rec/T-REC-G.989.1/e

[20] Y. Luo, X. Zhou, F. Effenberger, X. Yan, G. Peng, Y. Qian, and Y. Ma, "Time- and wavelength-division multiplexed passive optical network (twdm-pon) for next-generation pon stage 2 (ng-pon2)," *Journal of Lightwave Technology*, vol. 31, no. 4, pp. 587–593, 2013. [Online]. DOI: 10.1109/JLT.2012.2215841

[21] A. O. Maria, M. Yacelga-Pinto, and G. V. Arevalo, "Experimental evaluation of a ng-pon2 network," in *2018 IEEE Third Ecuador Technical Chapters Meeting (ETCM)*. Cuenca, Ecuador: IEEE, 2018, pp. 1–4. [Online]. DOI: 10.1109/ETCM.2018.8580339

[22] E. Brandon, A. Gladston, and J.-P. Blondel, "Cayman-jamaica fiber system," in *Proceedings of Optical Fiber Communication Conference (*. Dallas, TX, USA: Opt. Soc. America, 1997, pp. 60–60. [Online]. DOI: 10.1109/OFC.1997.719690

[23] J. Prat and D. Pla, "Remote amplification in high-density passive optical networks," in *Proceedings of 2005 7th International Conference Transparent Optical Networks, 2005*. Barcelona, Catalonia, Spain: IEEE, 2005, pp. 409–412. [Online]. DOI: 10.1109/ICTON.2005.1506186

[24] J. Latal, J. Vogl, P. Koudelka, J. Vitasek, P. Siska, A. Liner, M. Papes, and V. Vasinek, "Simulation and measurement of optical access network with different types of optical-fiber amplifiers," in *18th Czech-Polish-Slovak Optical conference on wave and quantum aspects of contemporary optics*, vol. 8697. International Society for Optics and Photonics, 2012, p. 86971U. DIO: 10.1117/12.2001263

[25] B. Chandru, J. Helina Rajini, and S. TamilSelvi, "Performance analysis of downstream transmission of 10gbps wdm pon using single and hybrid optical amplifiers," in *2014 IEEE International Conference on Advanced Communications, Control and Computing Technologies*, May 2014, pp. 828–832. DIO: 10.1109/ICACCCT.2014.7019208

[26] Z. Xiao, L. Yi, L. Xue, and W. Hu, "Single-fiber bi-directional burst-mode edfa for twdm-pon," *IEEE Photonics Journal*, vol. 10, no. 6, pp. 1–6, Dec 2018. DIO: 10.1109/JPHOT.2018.2873208

[27] Mun Seob Lee, Byung-Tak Lee, Bin Yeong Yoon, and Bong Tae Kim, "Bidirectional amplification with linear optical amplifier in wdm-pon," in *2006 Optical Fiber Communication Conference and the National Fiber Optic Engineers Conference*, March 2006, pp. 3–6.

[28] H. Hamadouche, B. Merabet, and M. Bouregaa, "Performance analysis and improvement of (2-10) gbps wdm pon using edfa amplifiers," in *020 1st International Conference on Communications, Control Systems and Signal Processing (CCSSP)*, May 2020, pp. 90–94. DOI: 10.1109/CC-SSP49278.2020.9151806

[29] G. Incerti, F. Incerti, F. di Vincenzo, D. M. Forin, G. M. T. Beleffi, F. Curti, A. L. J. Teixeira, and J. Prat, "Remote pumping and signalling in a passive optical network scenario," in *2008 10th Anniversary International Conference on Transparent Optical Networks*. Athens, Greece: IEEE, 2008, pp. 312–315. [Online]. DOI: 10.1109/ICTON.2008.4598799

[30] L. Marazzi, P. Parolari, M. Brunero, A. Giussani, R. Brenot, S. Barbet, and M. Martinelli, "80-gb/s conventional hybrid tdm/wdm pon with 256-split based on remotely-pumped network-embedded self-tuning transmitter," in *2012 38th European Conference and Exhibition on Optical Communications*, Sep. 2012, pp. 1–3. [Online]. DOI: 10.1364/ECEOC.2012.Tu.4.B.4

[31] Y. L. Yu, C. M. Peng, S. K. Liaw, Z. K. Lee, and C. C. Chen, "Bidirectional wdm pon with remote pumped gain flattening edfa by using cascading fbgs and lpfg," in *2015 International Symposium on Next-Generation Electronics (ISNE)*, May 2015, pp. 1–4. [Online]. DOI: 10.1109/ISNE.2015.7131982

[32] S. Hong, Y. Yu, S. Liaw, and C. Shin, "Pump reflector based remote pumped bidirectional edfa for wdm pon transport," in *2013 IEEE/CIC International Conference on Communications in China (ICCC)*, Aug 2013, pp. 195–198. [Online]. DOI: 10.1109/ICCChina.2013.6671113

[33] M. Jung, Y. M. Chang, and J. H. Lee, "A band-separated, bidirectional amplifier based on erbium-doped bismuth fiber for long-reach hybrid dwdm-tdm passive optical networks," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 4, no. 3, pp. 165–172, March 2012. [Online]. DOI: 10.1364/JOCN.4.000165

[34] L. Marazzi, P. Parolari, M. Brunero, R. Brenot, S. Barbet, and M. Martinelli, "Remotely-pumped network-embedded self-tuning transmitter for 80-gb/s conventional hybrid tdm/wdm pon with 256-split," *Optics Express*, vol. 21, no. 4, pp. 4376–4381, 2013. [Online]. DOI: 10.1364/OE.21.004376

[35] A. Baptista, M. Ferreira, A. Quintã, M. Lima, and A. F. Teixeira, "Remotely reconfigurable remote node for hybrid ring-tree passive optical networks," 2009.

[36] B. Schrenk, F. Bonada, J. A. Lazaro, and J. Prat, "Remotely pumped long-reach hybrid pon with wavelength reuse in rsoa-based onus," *Journal of Lightwave Technology*, vol. 29, no. 5, pp. 635–641, 2011. [Online]. DOI: 10.1109/JLT.2010.2101047

[37] R. Sifta, P. Munster, O. Krajsa, and M. Filka, "Simulation of bidirectional traffic in wdm-pon networks," *Przeglad Elektrotechniczny*, vol. 90, no. 1, pp. 95–100, 2014. [Online]. DOI: 10.12915/pe.2014.01.23

[38] P. C. Becker, N. A. Olsson, and J. R. Simpson, *Erbium-Doped Fiber Amplifiers: Fundamentals and Technology (Optics and Photonics)*, 1st ed. USA: Academic Press, 1999.

[39] R. Igarashi, M. Fujiwara, T. Kanai, J. ichi Kani, and J. Terada, "Raman amplification based 40 km reach 10g-epon for consolidation on the central office building," in *2019 24th OptoElectronics and Communications Conference (OECC) and 2019 International Conference on Photonics in Switching and Computing (PSC)*. Fukuoka, Japan: IEEE, 2019, pp. 1–3. [Online]. DOI: 10.23919/PS.2019.8818087

[40] L. B. Du, X. Zhao, S. Yin, T. Zhang, A. E. T. Barratt, J. Jiang, D. Wang, J. Geng, C. DeSanti, and C. F. Lam, "Long-reach wavelength-routed twdm pon," *Journal of Lightwave Technology*, vol. 37, no. 3, pp. 688–697, 2019-2-1. [Online]. DOI: 10.1109/JLT.2018.2850343

[41] C. DeSanti, L. Du, J. Guarin, J. Bone, and C. F. Lam, "Super-pon," *Journal of Optical Communications and Networking*, vol. 12, no. 10, pp. D66–D77, 2020. [Online]. DOI: 10.1364/JOCN.391846

Petr Munster was born in 1984, in Zlin (Czech Republic). He received his PhD at the Brno University of Technology, Department of Telecommunications in 2014 on the thesis entitled Parameters of the FTTx networks. His current research themes focus on fiber-optic sensors, especially distributed fiber-optic sensors, and on fiber-optic telecommunications. He has had approximately 50 scientific publications in journals and conferences in the last 5 years.

Tomas Horvath was born in Havirov, Czech Republic in 1989. He is a young researcher at Brno University of Technology and a researcher at CESNET. He received his PhD degree in communications and informatics from Brno University of Technology in 2017. His record shows more than 40 peer reviewed proceedings and journal papers. His current research interests include software-defined optical networking, passive optical networks, and sensing.

Petr Dejdar was born in Moravska Trebova, Czech Republic in 1993. He is a young researcher at Brno University of Technology. He received his EnG degree in communications and informatics from Brno University of Technology in 2018. His record shows more than 10 peer reviewed proceedings and journal papers. His current research interests include fiber-optic sensors, especially distributed fiber-optic sensors.

Edvin Skaljo received his PhD from the University of Tuzla, Bosnia and Herzegovina. He has more than 20 years of experience in telecommunications. He has held several management positions at BH Telecom, the leading telecom operator in Bosnia and Herzegovina. He has pioneered the implementation of numerous projects and new services in the field of fiber-optics communications and related broadband technologies. He is also an associate professor at the University of Sarajevo.