Journal of Optics
May 2013, Volume 15, Pages 1-9
http://dx.doi.org/10.1088/2040-8978/15/5/055703

Raman amplification in an optically high-powered data link dedicated to a 10 km long extension for submarine cabled observatories

F Audo[1], S Perhirin[1], V Quintard[1], M Guegan[1], A Perennou[1] and Y Auffret[2]

[1] Ecole Nationale d'Ingénieurs de Brest (ENIB), UMR CNRS 6285 Lab-STICC, Université européenne de Bretagne, Technopôle Brest-Iroise, C S 73862, F-29238 Brest cedex 3, France
[2] IFREMER, centre de Brest, BP 70, F-29280 Plouzane, France

*: Corresponding author : F. Audo, email address : audo@enib.fr

Abstract:

We describe a quasi-all-optical extension dedicated to simplifying the deployment of submarine cabled observatories. Based on power-over-fiber technologies, high power supply and data are both transmitted in one optical fiber of a few kilometers in length. We study the Raman amplification on the down- and up-stream data in the static regime with the high optical power varying from 100 mW to 4 W over a 10 km long single-mode optical fiber. We focus on the data optical budget and signal to noise ratio dependence with respect to the high optical power value and the data optical wavelength. We also present the transmission quality in the dynamic regime of this quasi-all-optical extension.

Keywords: Optical fiber network ; Optical power supply ; Power-over-fiber, Raman scattering ; Optical communication

1. Introduction

The exploration of oceans requires effective investigation means to provide information in many scientific domains. Among the existing solutions, the submarine cabled observatory networks allow to measure real-time and long-term data in a full-duplex configuration with a high bandwidth [1]. Furthermore, they can supply the instruments with a high power supply capability without time constraint. They are usually fixed structures and the deployment of theirs cables is expensive. Sometimes it could be interesting to extend the network in order to add instruments in a site of interest located a few kilometers away from the existing observatory with the best flexibility and the lowest cost.

In order to address this issue, we are developing an extension prototype only based on one single optical fiber which transports both the energy and the data exchanged between a submarine Junction Box (JB) and a sensor [2] such as a hydrophone, a seismometer, or a bottom pressure recorder. The JB is located near a node of the cabled network. This quasi all-optical extension could be deployed with a Remotely Operated Underwater Vehicle (ROV), which is a less expensive and a more flexible solution than the use of cable ships [1, 3]. We have shown previously the feasibility of such an extension: the energy and the down-stream data have been transmitted over one optical fiber of 10 km long [2]. The extension is designed to transmit bidirectional data with a bit rate up to 5 Mbit.s-1. This rate is compatible with commonly used oceanic instruments, like a hydrophone.

Usual applications using power-over-fiber are designed to transmit relatively low optical power supply (several milliwatts) over Single Mode optical Fiber (SMF) links up to 10 km long [4]. To our knowledge, only just one application was reported to provide an optical power supply of 2 W but only over 2 km [5]. We need in our system to provide several hundreds of electrical milliwatts to the instrument (sensor and interface). So, we raise a step in term of optical power over the fiber link as we use an optical power supply of 4 W in order to get enough electrical power at the instrument side. This high power over the used SMF generates of course non-linear phenomena like the stimulated Raman scattering [6]. Hence, the feature of this work is to investigate the influence of the optical power supply till 4 W, on the down- and the up-stream data transmission budgets, which could offset or overcompensate for attenuation from the optical fiber and optical component losses. This study is necessary to optimize the data quality transmission and the electrical power available at the instrument. The originality of this work consists in the study of the simultaneous transmission of bidirectional data and optical power supply, higher than 1 W, over a 10 km long SMF.

In this paper, we first describe the experimental setup developed for our study. Then, we discuss about the optical phenomena, which likely could appear during the transmission of high optical power. Then, we characterize the experimental setup in static regime and focus on the Raman amplification of the signal, as a function of the wavelength and the optical power of the pump source. Finally, we characterize our quasi-all-optical extension in dynamic regime and we discuss about the observed phenomena.

2. Experimental setup

The experimental setup developed to study our quasi-all-optical extension is shown in figure 1. The extension is designed to connect the JB with the instrument. It is planned for long distances beyond 1 km and up to at least 10 km. To develop our prototype, we have chosen a 10 km long SMF because of its low attenuation in the range of telecommunication wavelengths. The photovoltaic power converter is built of InGaAs/InP and its optical/electrical (O/E) conversion efficiency is approximately -6 dB around 1500 nm [5]. The continuous High Power laser Source (HPS) is a Raman fibered laser and is able to provide 10 W (40 dBm) around 1480 nm. The down- and the up-stream data wavelengths can be set in the 1520-1580 nm range in our system. We have chosen data lasers which provide up to 10 dBm at 1550 nm for our test conditions. In the dynamic regime, these lasers are modulated by Mach-Zehnder modulators. Two Wavelength Division Multiplexing (WDM) couplers, located on the both sides of the optical fiber, are used to combine or to separate the two different wavelengths (power supply and data). The optical circulators are devoted to separate the down- and up-stream data. The O/E power conversion module is made up of one or more photovoltaic power converters. Two photodiodes, whose electrical bandwidth is 2 GHz, are used for the O/E data conversions, one for the data detection near the sensor and one inside the JB.

The measurements to characterize the extension are realized at some particular positions of the set-up labeled with a letter in figure 1: A_P (high power laser output), A_D (down-stream data laser output), A_U (up-steam data laser output), B (signal transmitted over the 10 km optical fiber), B_D (down-stream data output), and B_U (up-stream data output).

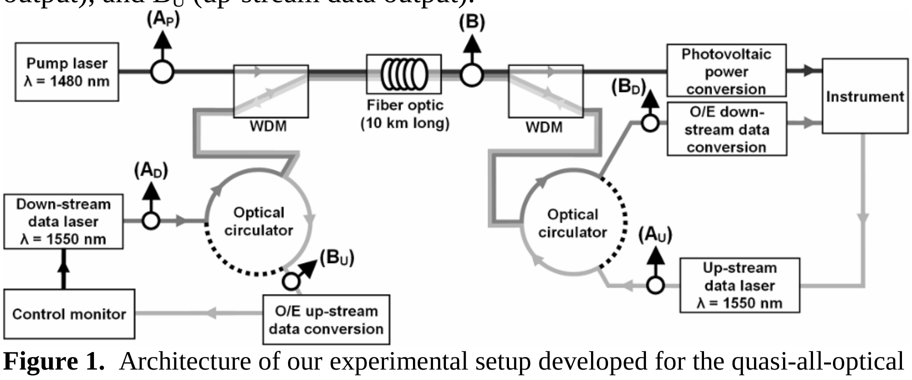

Figure 1. Architecture of our experimental setup developed for the quasi-all-optical extension.

3. Optical phenomena due to high power

The aim of the project is to obtain an electrical power of about a hundred of milliwatts for the instrument. Consequently, a high optical power has to be transported upon the fiber and this can induce some phenomena like damages or non-linear effects as for example Raman amplification. In the following, we describe the three main phenomena that we identified as being able to occur in our case.

3.1. Optical damages

The silica optical fiber is able to bear more than 10 GW/cm^2 [7]. Given that the SMF-28 has an 8.2 µm core diameter, it can withstand more than 21 W. However, if heat point, contamination or pressure appear on the optical fiber, this degradation threshold can greatly be decreased. For example, the end face of one optical connector can be damaged with dirt and contaminations [6]. Firstly, the contaminant absorbs the power. This leads to a local temperature increase, which can burn the connector end face. The damage causes excess optical losses between 50% and 70% [6]. The power of 1 W is enough to damage the optical connector end faces with a contaminant. Therefore, it is advised to avoid connectors in the context of the use of high optical power.

The second effect, we can mention, can occur with the propagation of high optical power along optical fiber with tight bending as it could burn the cable. Indeed, the high optical power propagates trough the fiber and leaks out of the core to the outer coating in the bent part. The coating material absorbs the power and the temperature increases. It may burn the cable and cause fire in the cable. Experiments have shown that the bending diameter must be more than 20 mm at 1 W and more than 30 mm at 3 W [8].

The last effect we have to speak about is the fiber fuse. It is due to the propagation of high optical power in the fiber, when there is a heat point, a contaminant or pressure. It results in a bright white visible light, propagating from the initiation point toward the laser source over more than 1.5 km long in certain cases. The fiber fuse melts and vaporizes the core, and creates periodical void structure [8]. The SMF-28 threshold power is equal to 1.4 W at the initiation point [8]. Solutions exist in order to suppress fiber fuse propagation: Hole-Assisted Fiber (HAF) and Photonic Crystal Fiber (PCF) [9]. Therefore, a section of HAF or PCF could be added in the system to secure it from fiber fuse.

In order to avoid all these effects, we choose to link components and fiber optic by fusion splicing and not by connectors.

3.2. Brillouin scattering

The Brillouin scattering creates a backward optical wave, with a Stokes frequency shift of 11 GHz (in an optical fiber SMF-28) [10]. Usually, the stimulated Brillouin scattering (SBS) limits the maximum optical power introduced in the optical fiber to several hundreds of milliwatts [11]. Moreover, the SBS causes the Raman gain saturation in the case of Raman amplification [10]. The SBS threshold power P_{SBST} is the input power at which the Stokes wave power is comparable to the input power [12]:

$$P_{SBST} = 21\frac{A_{eff}.\kappa_{SBS}}{g_{SBS}.L_{eff}}(1+\frac{\Delta\nu}{\Delta\nu_{SBS}}) \qquad (1)$$

where A_{eff} is the effective area of the optical fiber, κ_{SBS} is the polarization factor, $\Delta\nu_{SBS}$ is the Brillouin gain spectrum FWHM, $\Delta\nu$ is the input wave FWHM, g_{SBS} is the maximum Brillouin gain, and $L_{eff} = [1-exp(-\alpha L)]/\alpha$ is the fiber effective length with the length L and the attenuation α.

The last term in the equation (1) could be negligible if the laser FWHM is lower than the Brillouin gain spectrum FWHM [11]. In our experimental conditions, we use a Raman amplification laser source, whose FWHM is higher than 1 nm. Consequently, we have to take into account this laser FWHM to calculate the P_{SBST}. Furthermore, in our system conditions, the HPS FWHM changes and grows up from 0.2 nm to 1.1 nm when the HPS power increases from 20 dBm to 36 dBm. Consequently, thanks to the equation (1), we estimate that the P_{SBST} rises from 44.5 dBm to 52 dBm.

Our experimental measurements show that the backscattered power rises from 3.4 dBm to 26 dBm when the HPS power increases from 20 dBm to 36 dBm. This backscattered power is always lower than 10% of the input power, and it is not critical for the HPS and the optical components. Therefore, in our application, the SBS is not a limitation.

3.3. Raman scattering

The Raman scattering generates a Stokes shift around 13.2 THz in the SMF-28, and over a bandwidth of 5 THz [6]. Stimulated Raman scattering (SRS) is usually used to amplify signals, which propagate

in a long optical fiber. This amplification can be obtained over a broad spectral bandwidth if the signal wavelength is in the Raman gain bandwidth of the optical fiber [6], which starts just above the pump wavelength. Moreover, this Raman gain does not depend on the relative direction of the pump and signal waves. For example in our system, the pump wavelength is set at 1480 nm and we obtained a significant gain around 1583.1 nm. It should be also noticed that the Raman scattering can generate Amplified Spontaneous Emission (ASE) at 1583.1 nm, which may add noise on the signal.
We can calculate the Raman threshold power P_{SRST}, defined as the input power at which the Stokes power transferred from the pump wave is equal to the pump power at the output of the optical fiber, due to SRS [12]:

$$P_{SRST} = 16\,\frac{A_{eff}}{g_R . L_{eff}} \tag{2}$$

where g_R is the Raman gain. The power threshold is equal to 2.7 W (34 dBm) at 1480 nm in the case of a 1583.1 nm Stokes wave and a fiber length of 10 km. Consequently, in our application we will be near or over this threshold and it will be possible to take advantage of the Raman amplification for the data.

4. Measurements and discussions

4.1. Characterization of the transmission in static regime

In this section, the Raman effect occurring in our optical extension in static regime is presented. The first characterizations are devoted to study the influence of the HPS power on the data by measuring the optical spectra. Figure 2 presents an example of the superimposition of the data and the power in the same optical fiber in the down-stream data direction. The HPS power at 1480 nm is equal to 33 dBm and the data power at 1550 nm is set at 0 dBm. The optical spectra are measured thanks to an optical spectrum analyzer at the two points A_P and B reported in figure 1. The measured power levels at 1480 nm, 1550 nm and 1583 nm are obtained thanks to the power integration over the wavelength ranges of, respectively, 20 nm, 2 nm and 40 nm.

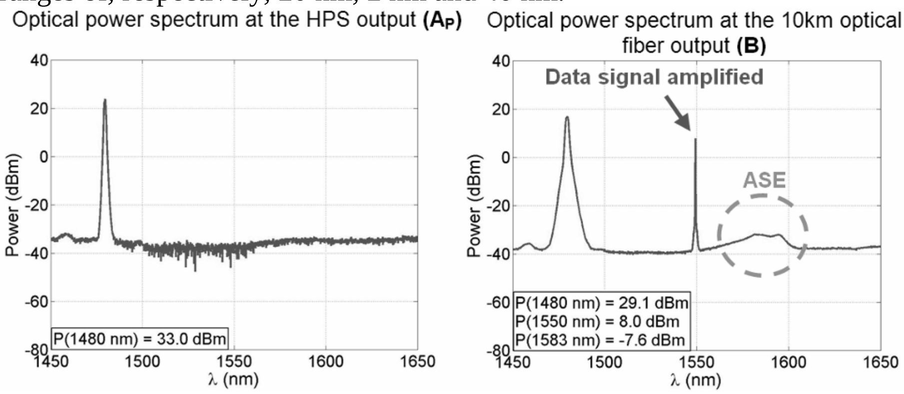

Figure 2. Measured optical spectra at points A_P and B along the optical fiber (P_{HPS} = 33 dBm and P_{Data} = 0 dBm).

We notice of course that the two waves are properly transmitted along the fiber as observed at the output of the fiber (point B). We can note the 4 dB losses of the HPS power due to the optical fiber attenuation and to the optical component insertion losses (coupler, WDM). As shown in figure 2, the measured data power at point B is 8 dBm while the data power at point A_D is 0 dBm. Consequently, the data signal has been amplified. Then, by assuming fiber attenuation over 10 km and components losses of about 3 dB, the data really benefits from an amplification of 11 dB. It is due to the stimulated Raman scattering [6]. We can also observe in figure 2 that the spontaneous Raman scattering is present at 1583 nm due to the high optical power propagation in the fiber.
In order to characterize more precisely this Raman amplification as a function of both the data and the HPS levels, for both data directions, we have measured the data optical budget. It is defined as the difference in dB between the data power at the experimental setup output (point B_D or B_U) and at the data laser output (respectively point A_D or A_U). The data total losses for these links are estimated at

about 11 dB. The optical budget results are shown in figure 3. The HPS power supply varies from 17 dBm to 36 dBm for a fixed data power level (–10 dBm or 0 dBm).

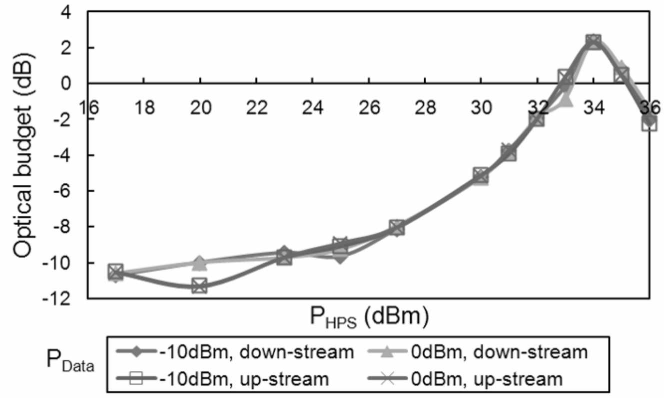

Figure 3. Optical budget, for the transmitted data at 1550 nm, measured between A_D and B_D (for down-stream direction) and between A_U and B_U (for up-stream direction), as a function of the HPS power for two different powers of the data laser.

We can notice that the Raman amplification offsets the losses for a HPS power level of about 33 dBm. We note that this behavior is almost the same for the two data directions and for the two data optical powers. We note also that the gain remains quite low when the HPS power is lower than 25 dBm. Above this value and just before 34 dBm, the optical budget increases from about -10.5 dB to 2.5 dB. It reaches a peak of 2.5 dB for a HPS power of 34 dBm. Then, above 34 dBm, the optical budget fall is due to the decrease of the stimulated Raman amplification. In fact, in this power range, by observing the optical spectrum of our HPS, we can note that it provides a significant optical power around 1583 nm due to the spontaneous Raman scattering. This phenomenon is due to the basic principle of operation of our HPS laser [13]. Figure 4 presents an example of the obtained optical spectra when the total HPS power is set at 36 dBm. So, as a substantial amount of the power is transferred from 1480 nm to 1583 nm, less power is available for the stimulated Raman amplification at 1550 nm in the optical fiber.

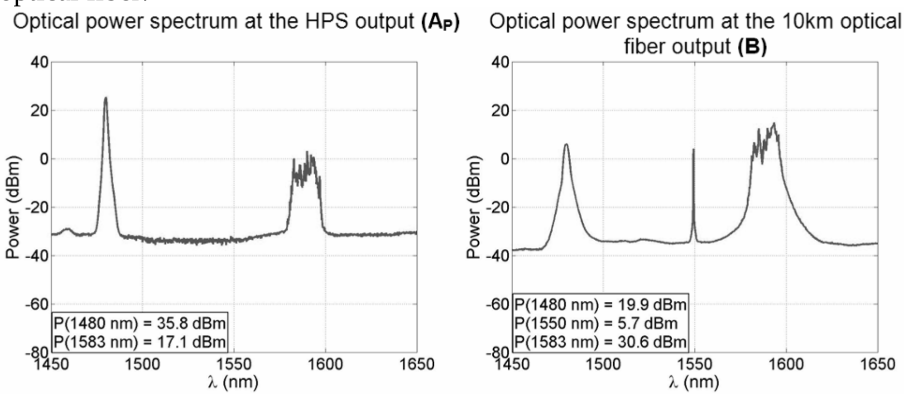

Figure 4. Measured optical spectra at points A_P and B along the optical fiber (P_{HPS} = 36 dBm and P_{Data} = 0 dBm).

In our application, it is important to benefit from this Raman amplification especially for the data up-stream direction (signal generated at the instrument location). Indeed, as we have to optimize the use of the electrical power delivered to the instrument, we should minimize the consumption of the data laser dedicated to transmit the sensor data toward the shore station. Our solution is to emit the minimum optical power as possible and to take advantage of the best optical budget for the up-stream data.

4.2. Raman amplification as a function of the down-stream or up-stream data optical wavelength

As we know that the Raman gain is higher at the frequency shift of 13.2 THz [6]–corresponding to the 1583.1 nm wavelength in our application–, it could be possible to obtain a better Raman gain if the data optical wavelength is set around 1583 nm.

In order to characterize more precisely the Raman gain as a function of the data wavelength, a tunable laser source replaces the 1550 nm data lasers. This source emits a power of –3 dBm for a wavelength which can be tuned in the 1540-1610 nm range. The measured powers (points A_D, A_U, B_D and B_U in figure 1) are integrated over a 2 nm width wavelength range.

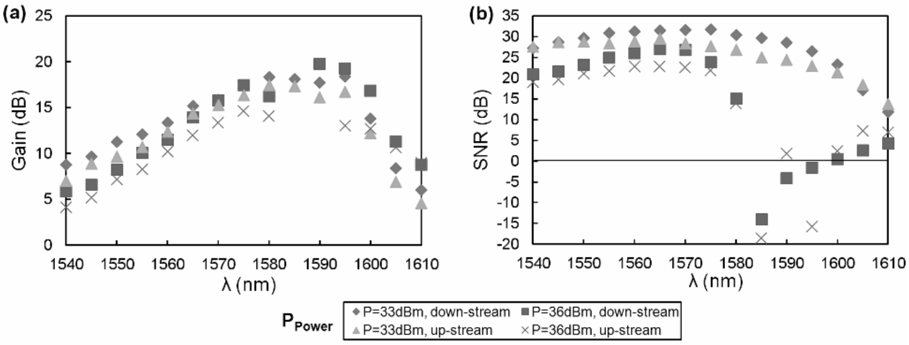

Figure 5. (a) Raman gain of the optical data and (b) Signal to Noise ratio of the optical data, transmitted in the 10 km long optical fiber, as a function of the data wavelength for two different HPS powers (P_{Data} = -3 dBm).

Figure 5(a) shows the measured Raman gain as a function of the data wavelength for two HPS powers (33 dBm and 36 dBm), and for the two data stream directions. The gain is calculated as the difference in dB between the data power measured at point B_D and A_D (respectively at B_U and A_U for the up-stream direction). The result is adjusted by removing the fiber attenuation and the optical component insertion losses. We can notice that the gain reaches a maximum of 20 dB around 1583 nm, corresponding to the Stokes shift imposed by the silica [6]. The obtained spectral response of the gain is very similar when the HPS power is increased from 33 dBm to 36 dBm. Furthermore, there are not significant changes of curve behaviors when the data wave co-propagates or counter-propagates with respect to the HPS power. Unfortunately, spontaneous Raman scattering is generated by the Raman HPS and created optical power around 1583 nm (figure 4). This power is amplified across the propagation in the fiber. Hence, there is a superimposition of the data signal and this amplified spontaneous Raman emission, which could noticeably decrease the extinction ratio and consequently degrade the data transmission. In order to estimate this potential degradation, we have measured the optical signal to noise ratio (SNR) as a function of the signal wavelength (figure 5(b)). The optical SNR is defined as the ratio between the data and noise power levels. These measurements are realized over a spectral bandwidth of 1 nm, centered at the data wavelength. We can observe that, when the HPS provides 33 dBm, the data remain properly detectable on a wide range of wavelength between 1540 nm and 1600 nm both for the up and down-stream data. But, when the HPS power is increased towards 36 dBm, the SNR behavior is drastically changed as the SNR decreases significantly after 1580 nm and becomes very low.

Therefore, we have to set the data wavelength near 1583 nm in order to benefit from the best data gain. In the case of the 1583 nm choice, the HPS power has to be limited to 33 dBm as beyond this optical power, the SNR falls drastically. But, as mentioned before, the instrument has to be supplied with the maximum optical power available. So, a compromise should be reached between the data gain and the SNR. That is the reason why, we have chosen a data laser emitting at 1550 nm sufficiently far from the amplified spontaneous Raman scattering emission bandwidth. Then, the down- and the up-stream data can benefit from a significant Raman amplification and the instrument gets the maximum power supply. Under these conditions, we have measured that the O/E power conversion module supplies about 160 mW of electrical power to the instrument.

4.3. Characterization of the transmission in dynamic regime

In this section, we study the data transmission quality and we discuss about the Raman amplification effects. Figure 6 shows the Bit Error Rate (BER) and eye diagrams measured at both outputs of the experimental setup, point B_D for the down-stream data, and point B_U for the up-stream data. The data signal bit rate is set at 150 Mbit.s^{-1} in order to realize measurements with a reasonable time and a measurement error of less than 10%. Three values of the HPS power have been chosen: 30 dBm, 33 dBm, and 36 dBm. The data are emitted with an average optical power of -5 dBm and a modulation index of 50%. The measurements are realized with a photoreceiver, with an electrical bandwidth from

DC to 210 MHz, and we attenuate the maximum incident optical power at -18 dBm, to be in the power range of the photoreceiver.

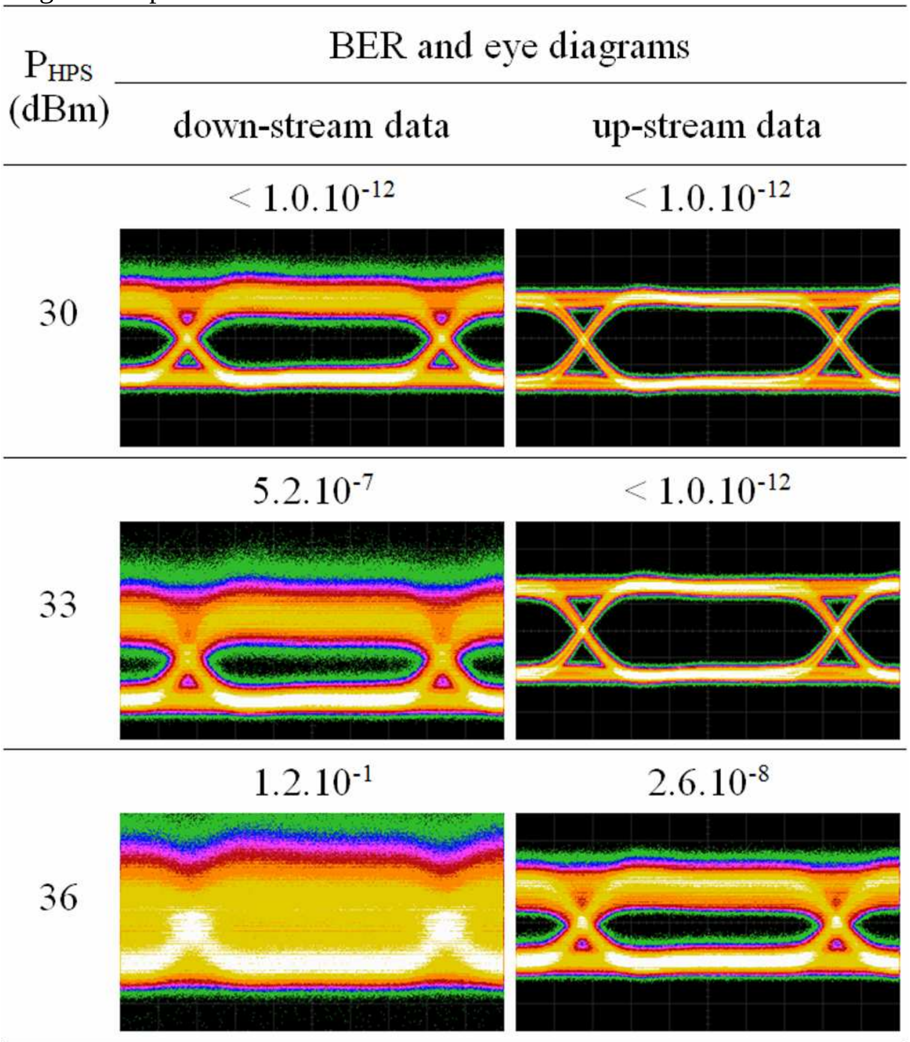

Figure 6. BER and eye diagrams measured at the B_D and B_U outputs of the experimental setup with a signal bit rate of 150 $Mbit.s^{-1}$.

We clearly observe, in figure 6, that the data quality decreases when the HPS power rises and this degradation can be attributed to the Relative Intensity Noise (RIN) transferred on the data [13]. Furthermore, the down-stream data are more degraded than the up-stream-data. Indeed, the RIN transfer depends on the relative direction between the Raman pump and the data, and then it affects more significantly the down-stream data [13]. For example, in the 33 dBm case, the down-stream data BER is about 5.10^{-7}, whereas the up-stream data BER is still less than 1.10^{-12}. However, the data signal quality remains quite satisfactory for the 33 dBm case.

As the target bit rate for our quasi-all-optical extension is 5 $Mbit.s^{-1}$, we have also qualitatively studied the transmission quality of a 5 MHz square wave, with an average power value of -5 dBm, as a function of the HPS power. Figure 7 shows the obtained signals at the B_D (down-stream data), and B_U (up-stream data) outputs of the experimental setup after the O/E conversion, respectively without and with 30 dBm, 33 dBm and 36 dBm HPS power.

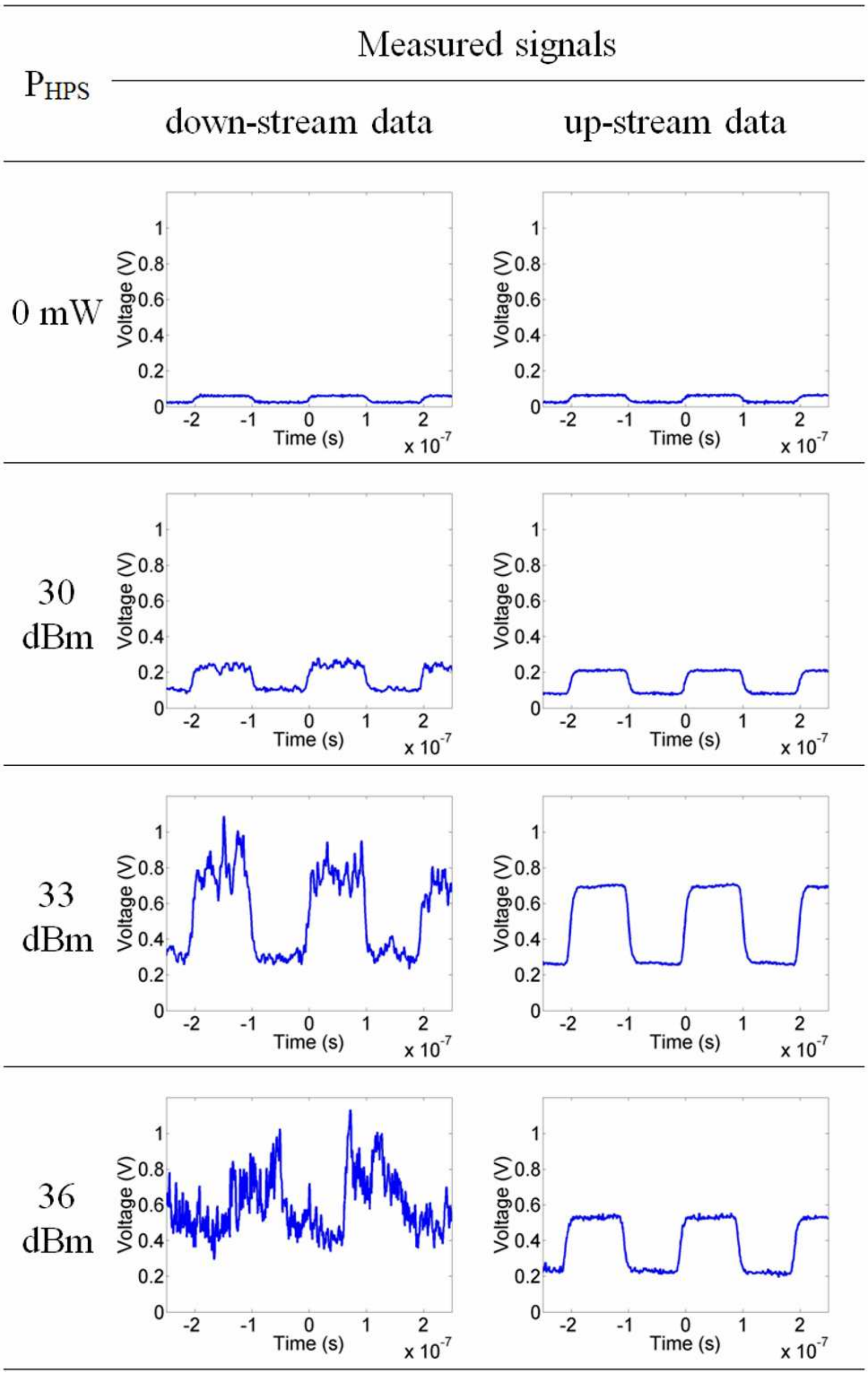

Figure 7. Measured signals after the O/E conversion at the output of the experimental setup (down-stream data: B_D, up-stream data: B_U), in the case of a 5 Mbit.s^{-1} bit rate.

As expected, we observe that the data are amplified in presence of the HPS power. The greatest amplification is obtained for the case of 33 dBm. These results are in agreement with the measurements of the optical budget, presented in figure 3. Otherwise, the down-stream data are more degraded than the up-steam data, and it is worse when the HPS power is at 36 dBm. These results bear out the study at a bit rate of 150 Mbit.s^{-1}.

In summary, the study in dynamic regime shows that, in our experimental conditions, it is better to restrict the maximum HPS power around 33 dBm to transmit data with a correct quality. This choice allows us to limit the impact of the RIN transfer.

5. Conclusion

We described the experimental setup of the quasi-all-optical extension developed in our laboratory and dedicated to simplify the deployment of submarine cabled observatories. Our prototype is able to transmit over one single optical fiber both the optical power supply of 4 W and the exchanged data, for an instrument located 10 km away from an existing cabled observatory. The characterization of our system, for the data transmission in static regime, has shown that we can take advantage of the stimulated Raman amplification, provided that a suitable choice of the data wavelength is made. In particular, we have brought to light that the spontaneous Raman scattering emitted by our Raman high power laser source around 1583 nm, can drastically reduce the SNR for a data wavelength too close to this value. We have chosen to set the data wavelength at 1550 nm. According to the obtained results in static and dynamic regime, we made a compromise between the Raman gain, the SNR of the data and the BER, in order to supply the instrument with the maximum optical power as possible and this, while keeping an acceptable data quality. All our characterizations have led us to determine that the best compromise for the HPS power is to set it at 33 dBm. In this condition, the electrical power supply reaches 160 mW, which is enough to supply the instrument. The down-stream data BER is about 5.10^{-7} and the up-stream data BER is lower than 1.10^{-12}.

The work in progress consists in improving the data quality, while conserving the same incident optical power on the O/E power conversion module. One way consists in shifting the down-stream data wavelength to improve their BER. Indeed, if the wavelength keeps away more from the Stokes wavelength, the Raman gain and so the RIN transfer will decrease. This change will involve modifications in the optical architecture in order to take into account this new third wavelength.

Acknowledgments

This work was supported by the GIS Europôle Mer, by the Brittany Region (FRANCE), and by the European Union (FEDER).

References

[1] Chave A D, Waterworth G, Maffei A R, and Massion G 2004 Cabled ocean observatory systems *Marine Technology Society J.* **38** 31-43

[2] Audo F, Guegan M, Quintard V, Perennou A, Le Bihan J, and Auffret Y 2011 Quasi-all-optical network extension for submarine cabled observatories *Optical Engineering* **50** 045001-1–045001-8

[3] Valdy P, Ciausu V, Leon P, Moriconi P, et al. 2007 Deep Sea Net: an affordable, and expandable solution for deep sea sensor networks *Symp. on Underwater Technology and Workshop on Scientific Use of Submarine Cables and Related Technologies (Tokyo, Japan, 17-20 April 2007)* pp 172–5.

[4] Werthen J G, Widjaja S, WU T C, and Liu J 2005 Power over fiber: a review of replacing copper by fiber in critical applications *Proc. of SPIE* **5871** 58710C-1–58710C-6

[5] Xu X, Cheung K K Y, Yang S, Liang Y, et al. 2010 Optically powered WDM signal transmission system with distributed parametric amplification *IEEE Photon. Technol. Lett.* **22** 1232–4

[6] Namiki S, Seo K, Tsukiji N, and Shikii S 2006 Challenges of Raman Amplification *Proc. of the IEEE* **94** 1024-35

[7] Kashyap R, and Blow K 1988 Observation of catastrophic self-propelled self-focusing in optical fibers *Electron. Lett.* **24** 44-7

[8] Seo K, Nishimura N, Shiino M, Yuguchi R, and Sasaki H 2003 Evaluation of High-power endurance in optical fiber links *Furukawa Review* **24** 17-22

[9] Hanzawa N, Kurokawa K, Tsujikawa K, Matsui T, et al. 2010 Suppression of fiber fuse propagation in hole assisted fiber and photonic crystal fiber *J. of Lightwave Tech.* **28** 2115-20

[10] Kobyakov A, Sauer M, and Chowdhury D 2010 Stimulated Brillouin scattering in optical fibers *Adv. Opt. Photon.* **2** 1-59

[11] Miyakawa H, Tanaka Y, Kurokawa T 2004 Design Approaches to Power-Over-Optical Local-Area Network Systems Appl. Opt. 43 1379-89

[12] Agrawal G P 2007 *Nonlinear Fiber Optics* (San Diego: Elsevier Academic Press)

[13] Headley C, Agrawal G P 2005 Raman Amplification in Fiber Optical Communications Systems (San Diego: Elsevier Academic Press)