POWER-OVER-FIBER FOR SENSORS IN SUBMARINE APPLICATIONS

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Abstract: A power-over-fiber system consists in transmitting power supply over an optical fiber to a remote electrical equipment. Based on this technology, we present a 10 km long quasi-all-optical architecture dedicated to transmit energy to a seafloor instrument, and to exchange data in a full duplex configuration in real time. In this paper, we experimentally show the feasibility of such a system. We introduce our experimental prototype and we discuss about its key features. We describe both the optical link and the low consumption electronic system in charge of the data management and we present the system performances.

1 INTRODUCTION

The power-over-fiber technology consists in transmitting an optical power beam through an optical fiber, to supply electrically a remote equipment, after the O/E (Optical/Electrical) conversion. This technology finds a renewed interest in recent years thanks to the development of more powerful HPLS (High Power Laser Source). Furthermore, it is possible to transmit over the same fiber the data exchanged between a control station and the remote instrument [1].

The advantages of the power-over-fiber technology are mainly due to the optical fiber's properties [1]. It is well known the standard silica optical fiber has a lower attenuation than an electrical cable for high bit-rate signal transmission. Moreover, in the case where a long length of cable is necessary, the low weight and the weak dimensions of the optical cable are interesting for the flexibility of the installation. Furthermore, one other interesting feature of such a fiber based system is to provide immunity to electromagnetic perturbations, electric shocks and lightening, what could be major advantages in hostile environments, for example where the use of an electric cable is banished.

By considering all the advantages of the power-over-fiber technology, we recently proposed [2] to use this technology to supply a low power seafloor instrument and to acquire data from its sensor. In order to address this issue we designed and developed a prototype whose architecture is in agreement with the following specifications to take into account the submarine environment: the power supply and the exchanged data have to use the same optical fiber in order to minimize the number of submarine optical connectors whose cost is prohibitive; the length of this optical fiber link could reach up to 10 km; the electrical power delivered at the instrument must reach some hundreds of milliwatts; the data transmission should be bidirectional, in real time and with a bit-rate of 5 Mbit/s. Moreover, the used communication protocol should be compatible with a large amount of low consumption instruments.

The aim of this paper is to show the experimental feasibility of this quasi-all-optical system. First of all, we describe the architecture of the prototype we developed and we argue about the technological choices we made. Secondly, we present the study of the optical link. We focus on the transmission efficiency of the optical power supply, and also on the quality of the data transmission. Then, we describe the electronic interface modules (station and instrument interfaces) linked to the power-over-fiber-system and in charge of the data management. It is designed to have the lowest possible consumption and to be the most generic as possible with the submarine equipment usually used. We also describe the communication protocol we set up between the shore station and the instrument interfaces. To conclude, we discuss about the possibilities, the constraints and the limits of such a system, and we talk about our main application.

2 ARCHITECTURE OF THE TEST PROTOTYPE

Figure 1 shows a schematic diagram of the quasi-all-optical architecture developed for the prototype we used for the tests.

The shore station and the instrument are linked by an optical fiber and two interface modules: the station interface and the instrument interface. These interfaces adapt to fit the electrical power and data to the optical link. They realize O/E or E/O (Electrical/Optical) conversions, and they manage the exchanged data.

The optical power (HPLS) and the "down-stream" data are transmitted from the station interface towards the instrument, both in optical domain. Then each optical wave is converted into electrical wave. The generated electrical power supplies the instrument and its interface too. On the other way, the sensor sends "up-stream" data to the instrument interface which converts them into optical form. These data are transmitted over the same optical fiber and they are converted into electrical data at the station interface, where they are managed and sent to a computer in the shore station.

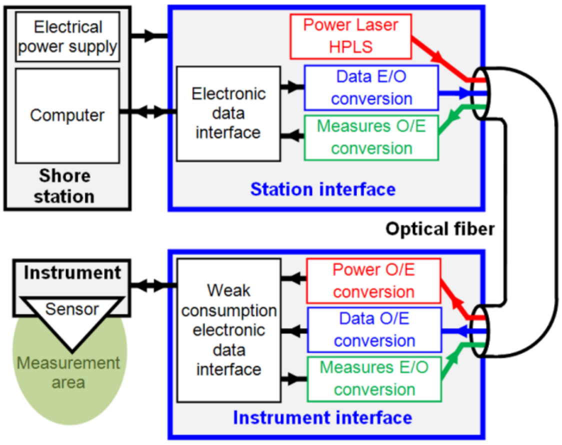


Figure 1: Schematic of the quasi-all-optical architecture.

We have chosen a standard single mode fiber SMF-28, because it is generally used in the field of optical telecommunications and usual optical components, needed for the experimental setup, are designed with this type of fiber [2].

In order to transmit data, it is necessary to define the communication protocol used between the station and the instrument interfaces. We have chosen the SPI protocol (Serial Peripheral Interface), as it is a synchronous protocol, widely used in the field of the submarine instrumentation.

The feasibility study of our proposed quasi-all-optical prototype is divided in two parts:

At first, we present the optical part which consists in studying the optical transmission of the optical power supply and the down- and up-stream data simultaneously. We must measure the optical losses and analyze the effects induced by physical phenomena occurring during the propagation in the fiber. Furthermore, we have to study the O/E conversion of the optical power supply and check the electrical power collected and available for the instrument; this latter must be more than 100 mW.

Then, we present the low power electronic system, which consists in developing the interfaces and studying them with respect to the quality of the data transmission and also their electrical consumption. Among them, the instrument interface must be a very low consumption module in order to remain compatible with the quantity of electrical energy that the power over fiber system can supply without obliging the HPLS to emit a too strong power [2]. Furthermore, the electronic circuits of the interfaces have to be developed in order to implement the SPI protocol for the link between these two interfaces.

In the following, we present the results about each part in two separate sections, and then we conclude about the feasibility of our quasi-all-optical system.

3 OPTICAL LINK FAISABILITY

3.1 Power transmission and conversion efficiency

The HPLS wavelength is chosen by taking into account a compromise between the optical fiber attenuation, the availability of continuous high-power fiber lasers and the photovoltaic power conversion efficiency [2]. We selected a Raman fiber laser, able to transmit 40 dBm (10 W) at a wavelength of 1480 nm. At this wavelength, the optical attenuation of the fiber is 0.3 dB/km, and the photovoltaic cells conversion efficiency is -6 dB (25%).

The experimental characterization shows that the optical budget, i.e. the optical losses due to components and the optical fiber between the input and the output of the optical link, are equal to -4 dB. Given the high optical power we use, an optical nonlinear phenomenon, the Raman ASE (Amplified Spontaneous Emission), plays an important role during the propagation [3]. The optical power delivered around 1480 nm is spectrally shifted near 1583 nm when the emitted power is higher than 33 dBm. This reduces significantly the optical power around 1480 nm and causes noise near 1583 nm. However, this spectral shift is not a problem for our O/E conversion module because we chose photovoltaic cells providing a large bandwidth of detection.

The O/E conversion is realized thanks to Photovoltaic Power Converters (PPC) from JDSU. Their optimal performances are reached with an incident optical power of 20 dBm. Above this power, the O/E conversion efficiency decreases drastically. As the incident optical power is higher than 26 dBm in our setup, the optical wave is spitted up in four parts, and sent to four PPC, linked together electrically in order to improve the conversion efficiency of the power O/E conversion module. In these conditions, the collected electrical power increases from 85 mW to 217 mW, when the HPLS emitted power increases from 30 dBm to 36 dBm (Table 1).

With this configuration, we succeed to collect more than 100 mW electrical power. In fact, the best choice (and also its limitation) concerning the optical power, that the HPLS has to emit, depends on the impact that the generated nonlinear effects have on the optical data during their propagation, as we will see in the following.

3.2 Data transmission quality

We set the data wavelength in order to benefit at best from the Raman amplification. Then, two laser sources, for the down- and the up-stream data, emit around 1550 nm.

The characterization of the experimental setup, without transmitting the optical power supply, shows that the optical budget is near from -11 dB for both the up and down data streams. This result suits well with our estimation made from the components optical losses and the optical fiber attenuation. Then, when the optical power supply is added, the data are amplified thanks to the SRS (Stimulated Raman Scattering).

The characterization shows that the Raman gain can compensate significantly the components optical losses and the optical fiber attenuation [2-3], when the power emitted by the HPLS is between 33 dBm and 35 dBm (Table 1).

P_{HPLS} (dBm)	P_{Elect} (mW)	Gain (dB)		SNR (dB)	
		down-stream data	up-stream data	down-stream data	up-stream data
30	85	5.2	5.5	29.5	28.9
33	160	9.9	10.3	32.5	28.8
36	217	7.8	8.8	26.1	20.9

Table 1: Characterization results obtained for the optical link.

For example, we obtain a gain of 9.9 dB for the down-stream data when the HPLS emitted power is 33 dBm. This leads to an optical budget of only -1.1 dB. So, in our power-over-fiber system, it is in our best interest to take advantage of this Raman amplification for the data transmission.

However, we have also to take into account the fact that the data can be disturbed by the Raman ASE and also degraded by the RIN (Relative Intensity Noise) transfer, when the HPLS power level becomes important. Firstly, Table 1 shows the results of the optical SNR (Signal to Noise Ratio) measurement made in the static regime. We noticed that the superimposition of the data signal (1550 nm) and the ASE (around 1583 nm) consequently reduces the SNR when the HPLS emits a power higher than 33 dBm. Secondly, Figure 2 presents the effect of the RIN transfer observed in the dynamic regime on the data. As expected, this phenomenon degrades greatly the down-stream data, which are co-propagating with the optical power, when the HPLS emits a power higher than 30 dBm. However, the data signal quality remains still satisfactory for the 33 dBm case.

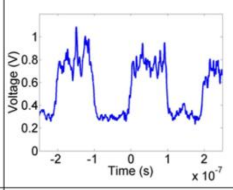
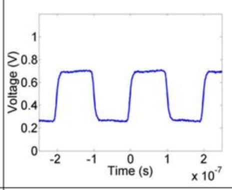
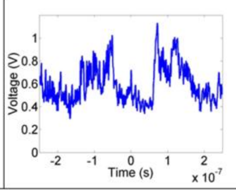
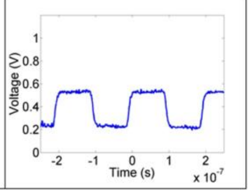
P_{HPLS} (dBm)	Measured signal after the O/E conversion at the instrument interface	
	down-stream data	up-stream data
33		
36		

Figure 2: Examples of the transmitted data obtained after the O/E conversion for two cases of the HPLS optical power supply, respectively set at 33 dBm and 36 dBm.

Under these conditions, we have to make a compromise between the Raman gain, the SNR of the data and the amount of the RIN transfer, 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 HPLS power is to set it at 33 dBm. This configuration leads to obtain the following performances: an electrical power supply of 160 mW; a SNR of 32.5 dB and a BER (Bit Error Ratio) of 5.10^{-7} for the down-stream data, and a SNR of 28.8 dB and a BER lower than 1.10^{-10} for the up-stream data, by considering the data lasers can emit a power between -10 dBm and 0 dBm. Of course this last choice interacts on the development of the low consumption modules constituting the interfaces.

4 DATA TRANSMISSION

As the power available to supply the equipment (the instrument and its interface) is only of some hundreds of milliwatts, attention should be paid to the low consumption of the instrument interface module. In order to reduce the electrical consumption of this device, the following requirements have been decided. First, we focus on the design of low-power circuits. Then, among several studied protocols, we opted for the SPI protocol which is commonly and widely used in the field of the submarine instrumentation, and easy to implement. Finally, we choose to dedicate our extension for low consumption instruments such as a hydrophone which do not receive control signal. So it allows the use of a three wires SPI as only three signals are then necessary (MISO: Master In Slave Out, SCLK: Signal Clock and /CS: Chip Select). Concerning the SPI protocol, we decided to attribute the slave's role to the instrument interface as it has a limited electrical consumption. So the station interface has been chosen to be the master.

To establish such a communication in our application, two main points had to be resolved.

The first one concerns the implementation of a three wires SPI using only a up-stream and a down-stream optical signals. To address this issue, we proposed a solution that we call "Quasi-SPI". It consists in using only two SPI signals, SCLK and MISO, and creating the /CS signal from the SCLK signal at the instrument interface.

The second point focuses on the use of a synchronous SPI protocol within a long-distance communication link of 10 km. Such a distance creates a critical delay between the /CS and MISO signals. In order to compensate this delay, the MISO signal goes through an electrical delay line which is calibrated at the initialisation process of the setup.

Figure 3 shows the protocols involved in our quasi-all-optical setup. The communication works as follows. A request of data is notified thanks to an Ethernet frame generated by a computer in the shore station. The station interface establishes a Quasi-SPI communication with the instrument interface by sending a SCLK signal. The instrument interface creates the /CS signal and provides all needed signals to start a SPI protocol with the instrument. The data collected by the sensors are encapsulated in a SPI frame and sent to the station interface thanks to the MISO signal. At the station interface, the MISO signal goes through a delay line which compensates the delay between the latter and the /CS signal. Once the station interface has read the received data, it encapsulates them in an Ethernet frame and replies to the computer.

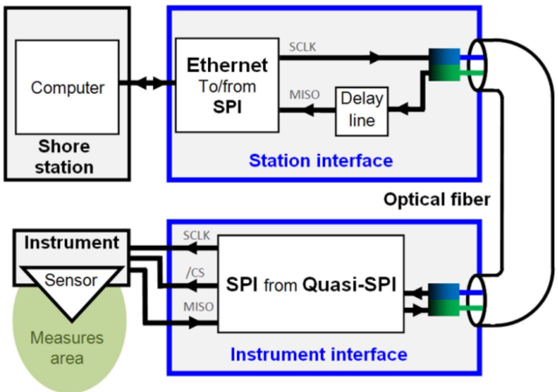


Figure 3: Protocols involved in the experimental setup.

Components involved in the station interface are a Sterralis ARM Cortex-M3 microcontroller and standard optical devices. To implement the delay line, a programmable FIFO is used. As said before, the instrument interface was developed in order to get a low consumption device. The main used components are a microcontroller MSP430 from Texas Instruments, and a transimpedance conversion module based on a low power AD8011 amplifier from Analog Devices. Besides, we developed a specific low power driver laser.

To operate our developed experimental setup the following characteristics were fixed:

- The SPI protocol works at 5 MHz (SCLK signal frequency).
- The SPI frames are 16 bits long.
- Ethernet frame contains 720 SPI frames.

We measured the electric consumption of the laser and its driver. They use 41 mW for an emitted optical power of -3 dBm. All the equipment (instrument interface and the instrument without sensor) consume 83 mW.

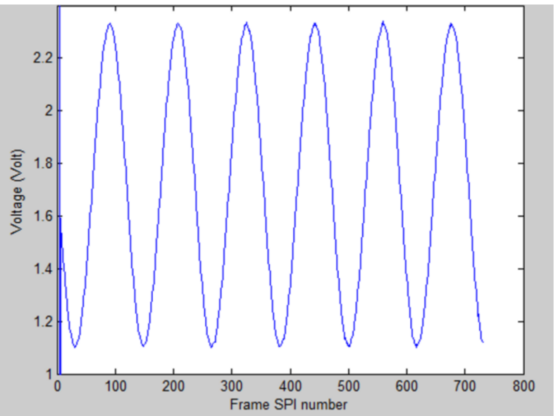


Figure 4: Sinusoidal signal collected with our setup and plotted with a Matlab application.

Experimental characterizations were realized to analyze the quality of the data exchanged between the equipment and the computer located inside the shore station. We used a sinusoidal generator to simulate the hydrophone. It provides a 1.7 kHz sinusoidal wave (80 mV p-p) to the instrument. As described before, the station interface collects the sampled data and transmits them to the computer after an Ethernet request. Then the data are extracted from the Ethernet frame and plotted thanks to a Matlab application. An example of the obtained results is presented in Figure 4. We can see the quality of the data transmission obtained with our prototype. The amplitude and the frequency are confirmed to be exactly the same as our setting. There is no visible distortion of the signal.

5 CONCLUSION

We described a quasi-all-optical architecture dedicated to supply and exchange data with a remote instrument located at 10 km away from a shore station. The optical power supply and the data are transmitted simultaneously over a single optical fiber. The characterizations have shown the feasibility of such a system. The electrical power available for the equipment (the instrument and its interface) can be higher than 100 mW. We have shown that Raman amplification can be used to amplify the data, but to the detriment of the quality of transmission under some conditions. A compromise should be made to transmit both the data, with a good quality, and the optical power, high enough to supply the instrument. Furthermore, we presented the low consumption electronic system developed for the instrument interface. We choose the SPI protocol at 5MHz and we have adapted it to the 10 km long optical link, consisting in only two stream optical signal. Finally, the instrument and the interface consume 83 mW, i.e. less than 100 mW, that corresponds to our specifications.

This work has been proposed for a particular application [2]: the extension of a cabled seafloor observatory. Indeed, the installation of an extension in order to reach a closed area of significant interest is difficult and expensive. The proposed optical architecture is a solution to extend them easily (with a ROV for example), and with the best flexibility and lower cost. The development of a submarine prototype based on our architecture is currently realized at the IFREMER.

However, this work could be useful for other applications, such as a submarine network deployment, composed of several optically powered sensors. Or, we might consider using this architecture in hostile environments, where the copper wire deployment has to be avoided [1] (oil tanker for example, where spark is a problem). To sum up, a quasi-all-optical architecture presents real advantages in the instrumentation field.

6 ACKNOWLEDGMENTS

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7 REFERENCES

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