Optical Communications: State of the Art and Some Activities in Brazil

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***Abstract*—This invited paper addresses the state of the art in optical communication systems. First, we present a brief historical account of optical communications. Next, we discuss several techniques to address the current capacity crunch in long-distance optical systems. Beyond the channel capacity increase by means of coherent communications, we also discuss the use of the alternative S and L optical bands, as well as spatial division multiplexing. Next, we address the multiple applications of Semiconductor Optical Amplifiers (SOAs), including amplification, wavelength conversion and spatial switching and discuss optical access networks, encompassing optical-wireless integration as well as the solution of the Fronthaul problem in 5G and 6G architectures. Finally, since Brazilian researchers have been active since the very early days of optical communications, the paper also presents an account of our contribution, focusing mostly on the activities conducted at the University of Sao Paulo (EESC-USP) and the University of Campinas (FEEC/Unicamp).**

Keywords*— *optical communications, optical amplifiers, SDM, SOAs, microwave signal distribution, 5G mobile fronthaul, WDM-PON.

I. Introduction

In a historical perspective, even ancient civilizations have made use of optical communications to convey information. Indeed, any communication scheme based on visual means, such as smoke signals, light beacons or mirrors, can be classified as optical communications. For instance, the use of shutters to selectively block a smoke signal is conceptually very similar to modern-day digital optical communications, albeit at a much smaller data rate.

The first optoelectronic communication system is the photophone, invented and patented by Graham Bell in 1880 [1]. In the absence of a suitable optical source, the optical carrier was provided the sun light itself. The speech signal to be transmitted modulates this optical carrier, by means of a flexible mirror. Finally, at the receiver end, the signal detected by a Selenium photocondutive photocell. In today´s parlance, the system would be called a free-space externally-modulated optical link.

In comparison to modern systems, what is missing is not only a coherent light source to replace the Sun but, also, a more suitable low loss propagation medium. Regarding optical sources, by the early 70´s, the use of the Liquid Phase Epitaxy (LPE) fabrication technique allowed the development of compact GaAs-based double-heterostructure semiconductor lasers for CW operation at room temperature in the near infrared [2]. Most important, the device could be directly modulated, since the output optical power changes in response to a modulated input electrical current.

Regarding the propagation medium, it had been proposed by Charles Kao in the mid-60´s that eliminating undesired impurities introduced during the fabrication process would bring fiber losses to a level low enough to allow practical use in long distance transmission [3]. Indeed, rapid progress followed and, by 1972, through the a Ge-doped silica core, a Corning research group demonstrated a fiber loss of about 4 dB/km. Just 5 years later, losses of about 0,2 dB/km, close to the fundamental limit dictated by Rayleigh scattering, were reported [4].

In this context, of simultaneous availability of compact optical sources and low-losses optical waveguides, a new era of communications systems began, with a series of seminal field trials, the first one by AT&T, deploying a link at 45 Mbits/s in downtown Chicago , in April, 1977.

After this brief historical account, in the next sections we will address the state of the art concerning the ever present need to increase the transmission capacity in optical communication systems. In section II.A we discuss the increase in data rate per channel. From the humble beginning of 45 Mbits/s, the development of coherent DSP techniques has allowed transmission rates as high as several hundreds of Gigabits/s per channel.

In section II.B, we address the efforts to fully utilize the low-loss spectral window in optical fibers. This trend started in the mid-90´s after the invention of the Erbium-doped fiber amplifier (EDFA) and the consequent implementation of the WDM technique and continues until today, with the L and S optical bands being explored for optical transmission. Next, in section II.C, we discuss the last frontier, which is the use of Spatial Division Multiplexing (SDM), with multi-core and/or few-mode optical fibers.

In the remaining of the paper, we first review the multiple applications of Semiconductor Optical Amplifiers (SOAs), including amplification, wavelength conversion and spatial switching. Next. we discuss optical access networks, encompassing optical-wireless integration as well as the solution of the Fronthaul problem in 5G and 6G architectures.

Finally, since Brazilian researchers have been active since the very early days of optical communications, the paper also presents an account of our contribution, focusing mostly on the activities conducted at the University of Sao Paulo (EESC-USP) and the University of Campinas (FEEC/Unicamp).

II. State of the Art in Optical Communications: Solving the Capacity Crunch in Long Distance Systems

A. Increasing the Data Rate per Channel

Early optical systems followed the TDM SDH/SONET digital hierarchy. This means that all the data rates employed are related to the basic data rate of a single voice channel, 64 kbits/s. Specifically, the basic building block of the SDH hierarchy is STM-1 (Synchronous Transport Module-1) at 155,52 Mbits/s. Along the years, progress occurred on a periodic 4-fold increase in data rates, always on the basis of the NRZ modulation format. Commercial systems had already reached 10Gbits/s (or more precisely 9,95328 Gbits/s) before the turn of last century, with the deployment of STM-64.

However, the next step, STM-256 (i.e., 40Gbits/s) was very prone to chromatic dispersion impairments, due to the higher data rate. This problem has motivated to investigation more advanced modulation formats, such as Duobinary and AMI, which still attract interest for free-space optical links [5].

Nonetheless, the technological alternative which eventually prevailed was a revival of coherent systems. The first generation of coherent systems has been intensively studied during the 80´s and early 90´s. In those early days, the goal was to improve the system performance, by placing an additional laser at the receiver, acting as a local oscillator. At the time, the technology did not achieve widespread use, due to the difficulties in achieving the required stabilization and phase match in the optical domain, between the local oscillator and the incoming signal [6].

In their revival, coherent systems are heavily based on digital signal processing (DSP) techniques, thereby eliminating the previous hurdles. In addition, coherent techniques allow full access to the electromagnetic field itself (instead of only the optical power, in case of direct-detection systems). As a consequence, it becomes possible to use phase-based high-order modulation formats. Indeed, initial commercial systems operated at 100 Gbits/s, using the QPSK format, with two orthogonal optical polarizations. It is worth mentioning that this new generation follows the Ethernet hierarchy, since a 160Gbits/s in the traditional SDH/Sonet hierarchy was unfeasible at the time. In any case, since then, the use of higher-order QAM formats has allowed the deployment of optical links operating at 800 Gbits/s using live fiber and commercial equipment [7].

B. Exploring the S and L Optical Spectral Bands

Despite all the progress in increasing the channel data rate, it can be said that the main factor behind the increased capacity of optical system is extremely low-loss optical window offered by optical fibers.

In fact, the idea of multiplexing several different frequency channel in the same transmission medium has been known since the early days of telecom systems, under the name of FDM (Frequency Division Multiplexing). The optical version is alternatively named WDM (Wavelength Division Multiplexing), since frequency and wavelength are directly related.

The usefulness of the WDM technique in the optical domain was recognized early on. However, the need to place optoelectronic regenerators, one for each wavelength channel, every 100 km or so, precluded its widespread practical use. A change of scenario was possible only after the Erbium-doped fiber amplifier (EDFA) was demonstrated in 1987. Rapid development of the WDM technology followed and, in the 1999 ECOC Conference, the Tbits/s barrier was overcome, by means of the simultaneous WDM transmission of 104 wavelength channels, each operating at 10Gbits/s.

Most commercial WDM systems operate in the C-band (1530-1560 nm) where the gain efficiency of the EDFA is the highest. However, to unleash the full potential of the low-loss window in optical fibers (1260-1675 nm, total bandwidth of 415 nm) it is necessary to have cost-effective amplifiers covering the spectral region encompassing S, C and L bands (1460-1625 nm).

Er-doped fibers can still be used in the L-band, by optimizing pump power and fiber length [8]. For the S-band the technology is much less mature. Hybrid amplifiers using a parallel-circuit configuration for thulium and erbium doped optical fibers (EDFAs) have already been implemented with good results [9]. However, Thulium-doped fluoride fibers are high-cost solutions and prone to problems concerning splicing and mechanical reliability.

As an alternative, and contrary to conventional wisdom, some years ago, we demonstrated EDFAs operating in the S-band. The key is to suppress the C-band ASE in such way to increase the gain at the S-band. More specifically, we demonstrated two ways to do so. The first is to employ a specialty erbium doped silica fiber, based on a depressed cladding refractive index profile in order to provide a high attenuation cutoff filter for wavelength above 1530 nm and allow S-band amplification [10] The second is to use a conventional Er-doped fiber, followed by a C-band rejection filter [11].

A schematic of the all-EDFA triple band S-C-L amplifier is given below. The amplifier is composed by three distinct optical paths, one for each specific wavelength band. A more complete account of the principle of operation for this specific EDFA is beyond the scope of this review paper. More details can be found in [12].

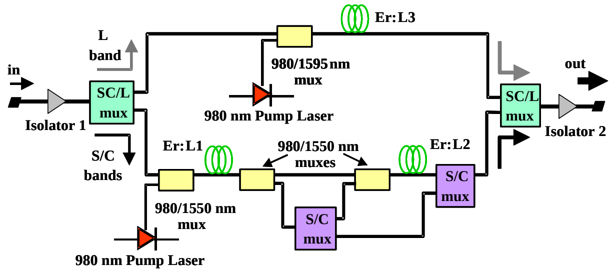

Fig. 1. Schematic diagram for the triple-band EDFA.

Optical fiber amplifiers can also be used in the O-band (1260-1360 nm). Traditionally, the O-band has been the realm Praseodymium (Pr) doped ZBLAN glass fluoride fibers. More recently, Bismuth doped glass (including silica) fibers have been providing good results and are more likely to find widespread use [13].

Other types of amplifier are also available. Raman amplifiers can operate in any wavelength range, but require a combination of high-power optical pumps to achieve operation over a wide optical band [14-15]. Finally, semiconductor optical amplifiers (SOAs) can be made very wideband. Also, as it will be addressed in more detail in the next section, their very high non-linearity and fast gain dynamics are very useful for applications such as switching and wavelength conversion. Nonetheless, these same features can be somewhat detrimental for the SOA as an in-line amplifier.

C. Using Spatial Division Multiplexing (SDM)

The more recent frontier to increase system capacity is Spatial Division Multiplexing (SDM). Regarding submarine cables, SDM usually means to reconfigure the optical cable, by using, for instance, thinner polymer coatings, to accommodate a larger number of optical fibers.

More recently, the optical communications community started using the same term to comprise either multicore (MC) or few-mode (FM) optical fibers. In the case of multicore fibers, the goal is to arrange several optical fiber cores in some sort of 2-D grid in the same optical fiber, in order to increase capacity. To assure compatibility to standard single-mode fiber, the total cladding diameter must be kept at 125 microns. In consequence, some coupling between cores is inevitable. However, these problems can be addressed by fairly low-complexity DSP MIMO techniques.

More challenging are the few-mode (FM) optical fibers, in which a few group modes (typically 4-6) propagate simultaneously through the fiber, each one carrying its own bit stream. In this case, mode coupling is much more severe but the problem can still be tackled by a MIMO receiver.

The use of both techniques can produce quite impressive transmission results. For instance, during the last OFC conference, it was demonstrated 372.8 Tb/s of unrepeated transmission over 213.3 km link using a 4-core multi-core fiber with standard cladding diameter and bidirectional Raman amplification. More specifically, the authors reported transmission of 424×24.5 GBaud PM-64QAM signals in the C+L bands for a capacity-distance product of 79.5 Pb/s·km [16].

Multicore have gained some ground in data centers but there are several practical problems, which must be solved before such fibers can find widespread use in long-haul systems. Among those challenges there are obviously splicing and coupling, but also signal amplification, particularly in the case of few-mode systems.

This is because, for longer distances, the EDFA remains crucial to overcome the optical propagation loss. However, the use of conventional single-mode EDFAs does not assure modal gain equalization since each mode will experience a distinct optical gain value, due to their distinct optical intensity distributions. This absence of gain equalization may severely impair the system performance and makes the design of a few-mode amplifier (FM-EDFA) much more complex than conventional EDFAs. The research group at EESC/USP was one of the pioneers on the design of optimized FM-EDFAs based on ring-core or double-ring core doping [17-18] as depicted below.

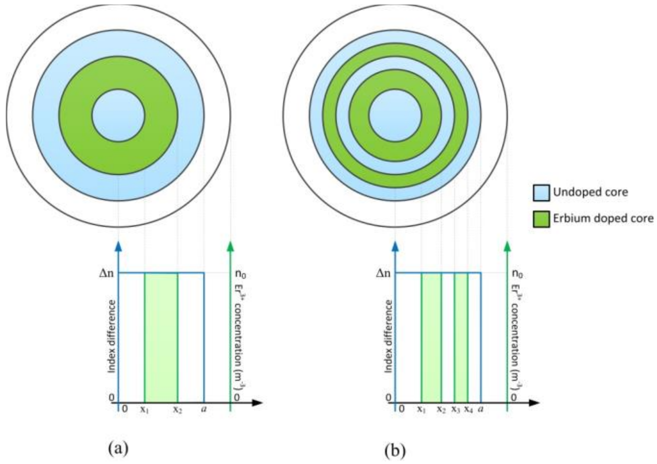

Fig. 2. FM-EDFA optimized doping profiles.

III. Applications of Semicondutor Optical Amplifiers (SOAs)

SOAs were initially designed to amplify optical carriers using a current-controlled small-signal gain optical amplification. However, commercial devices were only available after the development of traveling wave SOAs. These diode amplifiers have efficient and broad band antireflection coatings at the input and the output ports of the active optical channel waveguide, were the light amplification takes place. Later, advances in heterojunction devices made possible the introduction of SOAs whose gain was independent of the incoming light polarization. Also, beyond providing modulated optical carriers amplification, SOAs can be used in several applications such as wavelength conversion [19], routing [20], chromatic dispersion management [21], amplification of WDM signals [22], microwave down-conversion [23], data erasure and optical amplitude modulation extinction [24], all-optical memories [25], logical gates [26] and optical sensing [27].

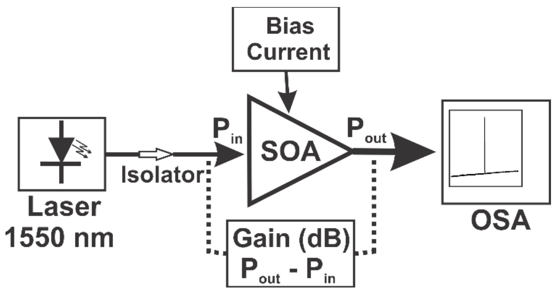

Fig. 3. Block diagram for the experimental setup.

The SOA modelling has been the subject of many papers. As an example, we were able to reproduce the output characteristics and the general SOA behavior, through extensive simulations, with satisfactory agreement to the experimental data of commercial devices. The experimental setup is shown in Fig. 3, where OSA stands for Optical Spectrum Analyzer. The simulation procedure combined adjustments of many SOA parameters, including the SOA active region width, thickness, confinement factor, linear gain coefficient (set to optimized values 2.5 μm; 100 nm; 0.17; $8.7 \cdot 10^{-20}$ m^2 respectively) , among others. The experimental and numerical results display good agreement after our calibration procedure (for the gain vs. current and gain vs. P_{in} curves) as shown in Figs 4 and 5 [26]. The method can be applied for different SOAs, enabling more accurate numerical predictions for black-box devices.

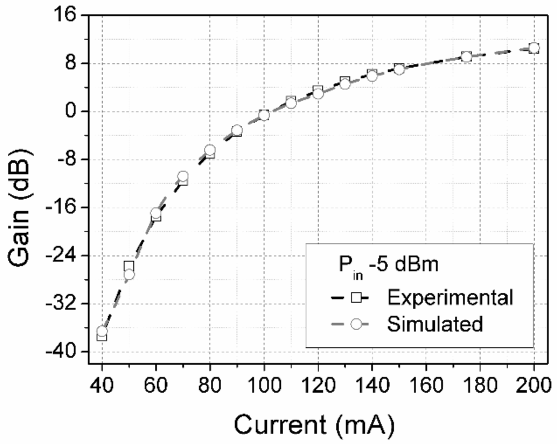

Fig. 4: Gain curve vs. bias current for the calibrated model and the experimental results for P_{in} (a) -5 dBm

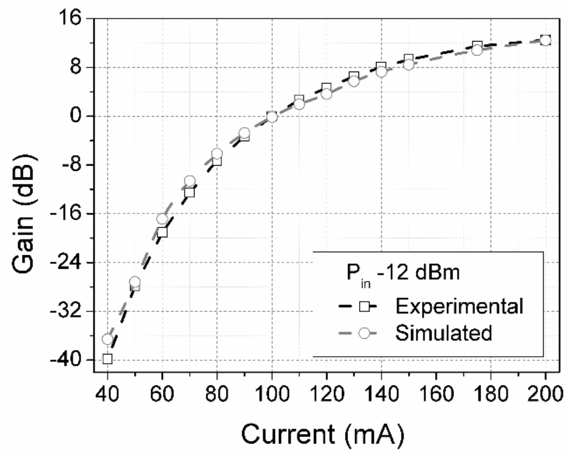

Fig. 5: Gain curve vs. bias current for the calibrated model and the experimental results for P_{in} = -12 dBm

In addition, we investigate the use of SOAs to solve the challenge of fast switching of intra-data traffic in data center networks (DCNs), with reductions on cost and energy consumption/bit. [29-33].

Nowadays, due to their small footprint, SOAs can be part of a photonic integrated circuits (PICs) [34]. Indeed, SOAs also present quite useful features, such as low power consumption, several wavelength including C+L bands, large dynamic range, broadband of 30 nm or more, fast response, and strong nonlinearities.

One of the SOA nonlinearities is the chirp, when a fast electrical gain-control signal changes the SOA gain. The chirp appears as a fast shift in the wavelength of the signal to be amplified. The SOA chirp can be used in combination with the optical fiber dispersion to improve optical pulses parameters. For instance, experimental shape variations of short microwave pulses can be achieved using a nonlinear 1550 nm SOA amplification and self-phase modulation (SPM). The proper setting of the SOA parameters produced nonlinear amplification of short pulses (up to 10 ps rise times), embedded in an adjustable window (from 333 ps to 1 ns). These SOA pre-chirped pulses were transmitted in a buried optical fiber (up to 18 km) followed by photodetection. The interaction of the pre-chirped pulses and fiber dispersion modified the received signal shape, extinction ratio, and rise-time, as shown in Fig. 6, where a 12 GHz microwave carrier was embedded in a gate-width of 250 ps with a pulse repetition frequency (PRF) of 2 Gb/s. Given a period of 83.3 ps for the 12 GHz sine wave, just 3 RF cycles are enough to fit the 250 ps gate, as noted in Fig. 5. Also, the red dotted line signal is the chirped pulse just after the SOA. Note the typical distortion due to SPM of the dotted line chirped signal.

The continuous line of Fig. 6 shows the same signal after propagation in a standard fiber of 18 km. After 18 km of fiber propagation, an improvement on the signal shape can be observed. However, the received signal displays distortions during the rise time of the internal pulses, shown by the letters A and B in Fig. 6. This behavior might be due to an over correction of the pulse shape, since the longer fiber provides greater dispersion and additional attenuation, on account of the 18 end fiber connectors [35]. Also, the SOA chirp could affect the integrity of the amplified signal, and we measured the SOA chirp due to electro-optical gain switching [36].

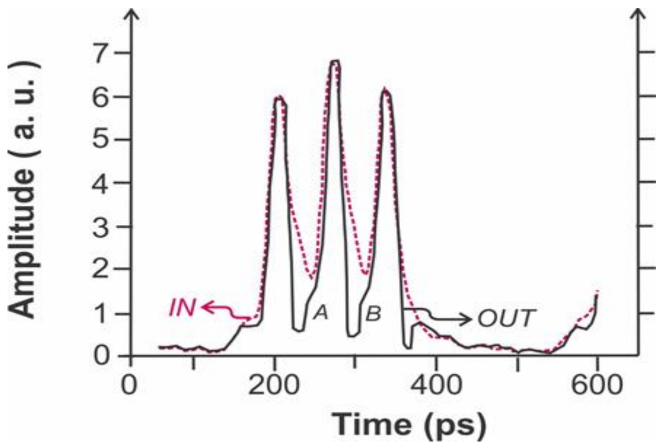

Fig. 6: Photo-detected signals for a 12 GHz microwave carrier after the SOA (red dotted line) and after 18 km of fiber propagation (continuous line).

Recent works employ SOA switches in combination with very fast tunable laser [37] to achieve wavelength routed optical switching. In those applications, the SOA electro-optical switching time was optimized employing artificial intelligence, achieving a record wavelength switch times below 900 ps across 6.05 THz (122×50 GHz) of continuously tunable optical bandwidth [38-39].

As a final remark, it should be pointed out that the prices of SOAs have decreased fostering their use in optical access networks, as shown in the following Section.

IV. Optical access networks and optical wireless integration

Optical access networks have been deployed worldwide in recent years, driven by present and future disruptive demands for bandwidth-hungry services and applications, such as video-streaming, cloud computing and the rising of the metaverse, among others.

The prevailing architecture is a point-to-multipoint passive optical network (PON) configuration, in which the downstream optical signal power transmitted by the OLT (Optical Line Terminal, at the CO) travels through a single feeder fiber before being divided by a passive optical splitter, in order to simultaneously broadcast to a large number of end users (Optical Network Terminals, ONTs). In upstream transmission, the optical splitter becomes a power combiner and the several ONTs are assigned to specific time slots, by means of some form of time TDMA protocol.

The standardization of the Gigabit Capable Passive Optical Network (G-PON) by the ITU-T was completed in 2009. Since then, efforts have been placed on the increase of the data rate provided by the TDM technologies. Those efforts resulted on both the 10 Gigabit Capable Passive Optical Network (XG-PON) as well as the Time-and-Wavelength Division Multiplexing Passive Optical Networks (TWDM-PON) in a relatively short period of time (2010– 2015). The more recent TWDM-PON standard, widely known in the literature as NG-PON2 is designed to aggregate up to eight independent channels, each one carrying up 10 Gb/s (80 Gb/s network capacity overall).

It is worth mentioning that in the late 90´s our research group at EESC/USP pioneered the investigation of an optical receiver similar to today´s NG-PON2 [40]. However, at the time, we devised a fairly complex dynamic bandwidth allocation scheme in the wavelength domain, requiring fast tuning (ns range) for the tunable optical receivers. Since those fast tuning speeds cannot be attained with conventional optical filters the goal was to design a tunable receiver architecture, without tunable optical filters. Specifically, in our design, the incoming wavelengths were demultiplexed in the optical domain and photodetected, each wavelength by its own PIN photodiode. In other words, the tunable optical filter is replaced by a fixed demux and an array of PDs. Next, a electronic selector circuit composed by FET microwave switches and a transimpedance amplifier selects the wavelength to be processed (see Fig. 7). The work was carried out in collaboration with the University of Rome, Tor Vergata, and both 4x1 and 16x1 circuits were successfully demonstrated, with tuning times smaller than 2 ns [40].

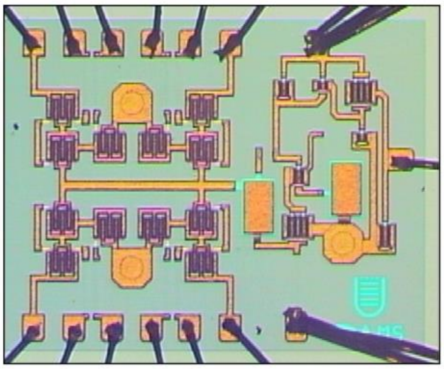

Fig. 7: Photo of the electronic channel selector circuit, part of an optoelectronic receiver for WDM-PON [40]. To the left, four microwave switches (3 FETs each, in a π–shaped connection) select the detected wavelength to be amplified by the transimpedance amplifier (right side).

Indeed, even though the network operator Verizon has announced a large scale deployment, the lack of low-cost optical filters has been hindering the widespread adoption of NG-PON-2. As a consequence, the PON industry has recently focused attention on the 25G (direct detection) and 50G (coherent detection) standards, one of which should be next technological step.

Nevertheless, it is unavoidable that, at some point in the future, the use of multiple wavelengths in the network will again be pursued, in the so-called WDM-PON architecture.

The main issue preventing widespread WDM-PON dissemination has always been the need for each ONT to have its own upstream wavelength. The simplest solution, to use fixed wavelength transmitters, excessively increases operational costs, given that a high number of different laser devices (equaling the number of wavelengths in use), must be kept in stock by the network operator.

This problem has been identified since the very early days of WDM-PON research. The answer is to develop *colorless* sources, in which the same hardware is used to generate any wavelength required by the network. Since tunable lasers (most promising options are tunable VCSELs) are still under development, over the years, several research groups around the world have investigated alternatives.

In our pioneer work on the self-seeding technique [41-43], we developed a WDM-PON architecture (Fig. 8, previous page) in which self-seeding occurs in Reflective SOAs located at the OLT, allowing upstream transmission based on wavelength reuse and carrier remodulation at the ONT. The remodulation scheme allows the use of a single wavelength for both bit streams, enabling more efficient sharing of the optical spectrum. As explained in the previous Section, downstream data erasure is achieved by operating the RSOA in deep saturation. Crosstalk between downstream and upstream data streams can be further minimized by using distinct extinction ratios in each direction, as well as by proper electronic hardware at the ONT [41-42].

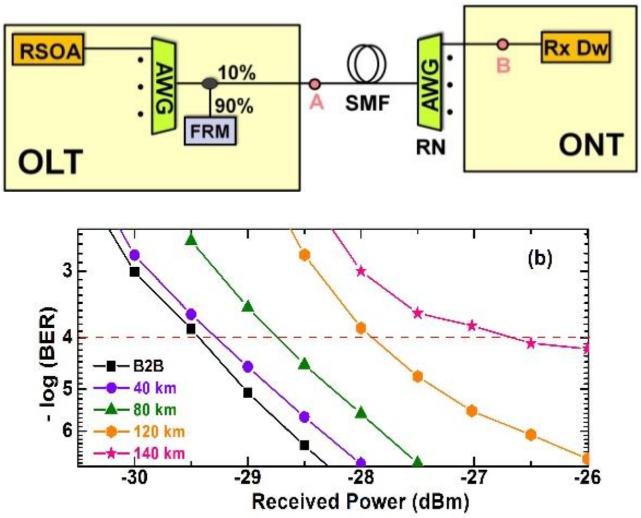

Fig. 8: **Top (a):** Self-seeding architecture where FRM is the Faraday rotator mirror, the reflective element used to avoid instabilities caused by polarization fluctuations**. Bottom (b)** BER optical transmission measurements up to 140 km [44].

More recently, we have been investigating the use of our WDM-PON topology for a 5G analog fronthaul [45-46]. There has been experimental demonstrations combining self-seeding techniques and CPRI-based digital RoF (D-RoF) transport for mobile applications in real-life scenarios [47]. However, in these cases, the D-RoF signals are digitalized into IQ samples, requiring a very large bandwidth. By contrast, our option for the Analog Radio-over-Fiber (A-RoF) is a much less complex fronthaul alternative because mobile signals are optically distributed in their original waveforms by a RF carrier over the fiber, in such way that the effort regarding signal processing and bandwidth requirements can be drastically reduced.

In fact, the rising of 5G has brought about a variety of of optical-wireless integration schemes. A full account of some of the possibilities, in the framework of a collaboration between the WOCA laboratory at Inatel and EESC-USP, is beyond rhe scope of this paper but can be found in [48] .

V. Conclusions

This invited paper addressed the state of the art in optical communication systems. First, we presented a brief historical account of optical communications. Next, we discussed several techniques to extend the current capacity in long-distance optical systems. Finally, we focused on optical access networks, encompassing optical-wireless integration as well as the solution of the Fronthaul problem in 5G and 6G architectures.

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