O-Band 10-Gb/s Operation of a Reflective Semiconductor Optical Amplifier Based Self-Seeded Transmitter for Optical Access Applications

L. MARAZZI,[1] P. PAROLARI,[1] M. BRUNERO,[1] M. MARTINELLI,[1] P. CHANCLOU,[2] Q. DENIEL,[2] F. SALIOU,[2] S. D. LE,[2] G. GAVIOLI,[3] R. BRENOT,[4] S. BARBET,[4] A. MAHO,[4] S. A. GEBREWOLD,[5] D. HILLERKUSS,[5] and J. LEUTHOLD[5]

[1]Politecnico di Milano, DEIB–PoliCom, Milan, Italy
[2]Orange Labs, Lannion, France
[3]Alcatel-Lucent Italia, Vimercate, Milano, Italy
[4]III-V Lab, Marcoussis, France
[5]ETH Zurich, Zürich, Switzerland

1. Introduction

Wavelength-division multiplexed (WDM) passive optical network (PON) topology has been included as an optional solution for a next-generation access network (NGAN) as the standard choice made by telecommunications services providers and equipment suppliers. The NGAN will include as a primary solution both the time WDM (TWDM) and WDM point-to-point; multiple-wavelength PONs in which each wavelength is shared between multiple optical network units (ONUs) by using time-division multiplexing and multiple access mechanisms will coexist with multiple-wavelength PONs, providing a dedicated wavelength per ONU [1]. Point-to-point WDM PON connectivity is also appealing for

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Address correspondence to L. Marazzi, Politecnico di Milano, DEIB–PoliCom, via Ponzio 34/5, Milan, 20133, Italy. E-mail: lucia.marazzi@polimi.it

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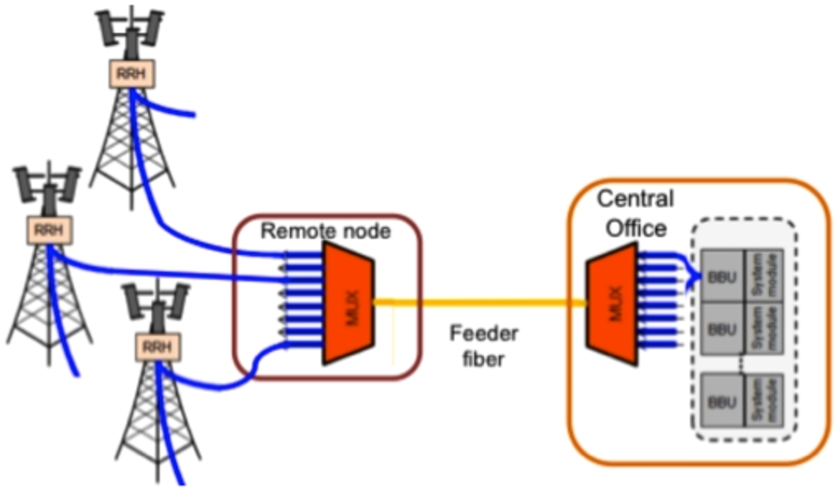

Figure 1. Possible point-to-point WDM PON solution for the fronthaul [2].

mobile applications, as it is actually able to provide a wavelength channel capacity higher than 1 Gbit/s, with the 10 Gbit/s target not far in the near future [2]. In particular, WDM PONs are a possible solution for the fronthaul, which requires a fiber network connecting remote radio heads (RRHs), located near the antenna, to the base band units (BBUs), located in base station hotels, as in the example in Figure 1. The link must support the common public radio interface (CPRI) standard, which has stringent low-latency requirements, symmetrical bit rates ranging from 0.6 to 10 Gb/s for up- and down-stream, and strong requirements on synchronization aspects. (Also among the possible solutions to achieve transport CPRI data, point-to-point fibers with array waveguide grating [AWG] have also been proposed, as shown in Figure 2 [3].)

Among possible WDM PON technologies, those based on colorless transceivers suppressing inventory issues prove very attractive. In particular, a colorless transceiver relying on self-seeded optical sources presents significant advantages, as it automatically and passively assigns the wavelength to the ONU without any external control to be exerted.

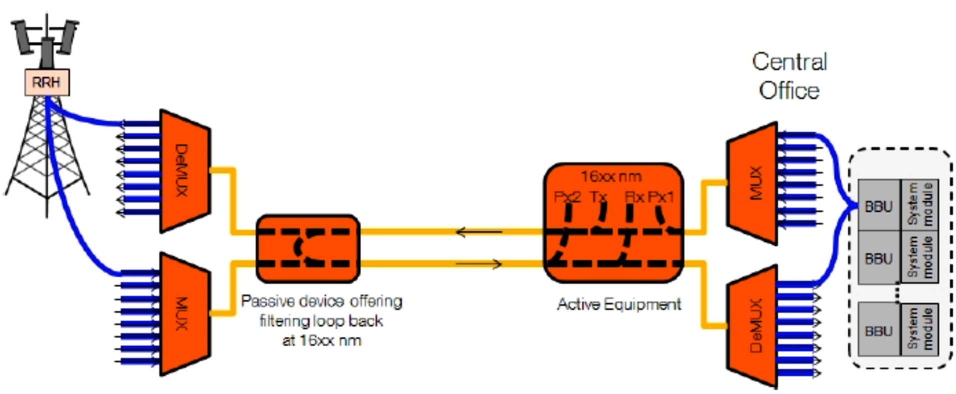

Figure 2. WDM network configuration to achieve passive monitoring at the antenna site.

The self-seeded approach based on reflective semiconductor optical amplifiers (RSOAs) offers self-tuning capability [4, 5] together with wide-bandwidth colorless operation. It also presents immunity to Rayleigh backscattering, which, on the contrary, is part of the process of the creation of the transmitted signal [6].

The aim of this work is to focus on the most recent results related to the self-seeded topology with particular regard to the impact of chromatic dispersion (CD) on the performance of these transmitters. In Section 2, a short description of the principle of operation of this transmitter and the main issues to be considered are given. In Section 3, some simulation results will be summarized to clarify the nature of CD impact on the transmitter performance. In Section 4, the characteristic of the new RSOA devices designed and realized by III-V Lab will be presented. Some experimental results at 10 Gb/s in the O-band will be discussed in Section 5, and finally, conclusions are drawn in Section 6.

2. Principle of Operation of the Self-Seeded Transmitter

A schematic of the transmitter is shown in Figure 3. While a more complete description of the principle of operation can be found in [7], it can be useful here to briefly describe it for the sake of clarity. In the self-seeded transmitter, a cavity is established between the RSOA mirror, located at the ONU, and a mirror placed after the filtering element, which is an AWG connected to the ONU by the drop fiber. The wavelength is thus automatically and passively assigned to the ONU, resulting in a colorless and self-tuning transmitter. The transmitter operation is based on the RSOA, which plays a key role: it provides the gain necessary for cavity build up and subsequent operation; it can directly be modulated, imprinting data on the carrier established in the cavity; and finally, thanks to its nonlinear properties, it bleaches the modulated signal, which recirculates in the cavity. As the proposed transmitter is embedded in the network, the built cavity may range, according to the drop fiber length, from a few tens of meters to a few kilometers of fiber, the unavoidable birefringence of which causes polarization fluctuations along it. These fluctuations, though slow, may cause the round-trip gain to drop, inhibiting lasing, when combined with the RSOA polarization-dependent gain (PDG). Adoption of a proper solution [8, 9] based on the retracing properties of the Faraday rotator mirror (FRM) has solved the problem of governing the signal state of polarization (SOP) evolution along the cavity. In the case of low-PDG RSOAs, a single FRM [10] is necessary, whereas for high-PDG RSOAs, an FRM with a Faraday rotator (FR) can ensure that the state of

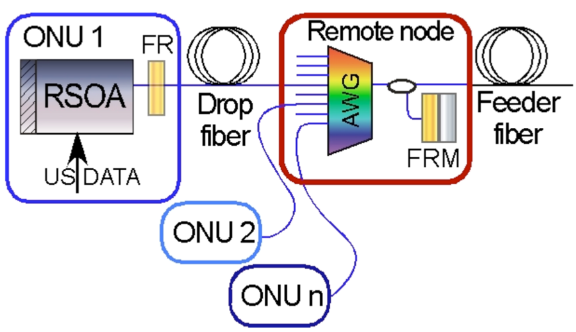

Figure 3. Schematic of self-seeded transmitter.

polarization (SOP) of the signal recirculating in the cavity and re-injected in the RSOA is aligned to the signal SOP at the RSOA output.

While the adoption of the two-FR configuration allowed stable transmitter operation up to 10-Gb/s, the 10-Gb/s measurements performed in the C-band pointed out a strong dependence of the propagation performance on the dispersive load [9], that is, on the CD characteristics of the feeder fiber, as shown in Figure 4, for two topologies exploiting a 110-GHz full-width half-maximum (FWHM) AWG and a 220-GHz FWHM AWG, respectively. The asymmetry is clearly evident in both cases. This can be justified easily by noting that a direct current modulation determines carrier density variation, which origins a chirp associated to the transmitted signal. It is worth noting that this behavior was already experimentally discussed in [11] in relation with the negative chirp associated with RSOA direct modulation. This chirp has been measured for the RSOA exploited in the present experiments, and it is shown in Figure 5 [12] together with the intensity of the signal obtained by direct modulation of the RSOA bias current. This chirp represents a limiting factor for standard single-mode fiber (SSMF) propagation at 10 Gb/s, as it interacts with the fiber CD and AWG transfer function. As a consequence, the feeder fiber maximum length, as well as the cavity length, i.e., the ONU distance from the remote node, are both deeply affected.

With the goal to reduce the amount of dispersion load burdening the performance of the transmitter, while reusing the optical distribution network (ODN), i.e., maintaining the SSMF, it has been natural to operate in the O-band, where SSMFs have minimum CD. This change is favored by the cyclic nature of the AWG, the transfer function of which is naturally replicated in the O-band, although as it will be shown that the FWHMs of the various channels are different, i.e., larger. Yet the main effort is placed in the design and realization of RSOAs with the proper characteristics of gain and nonlinearity.

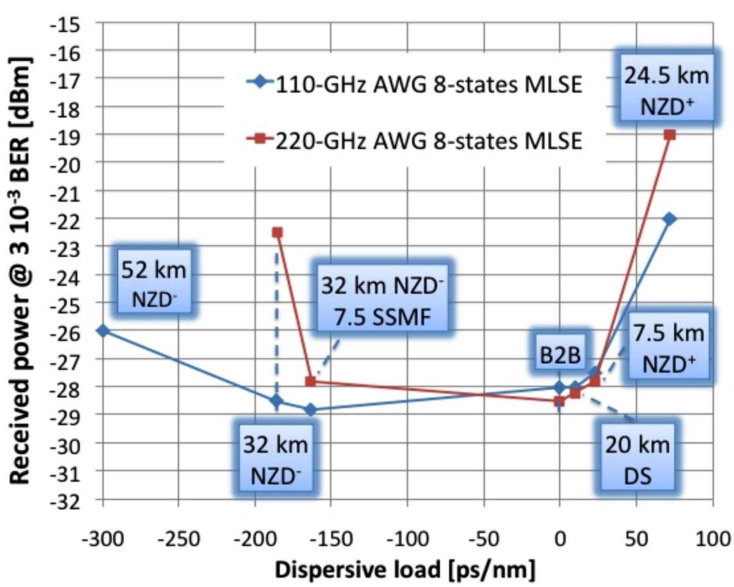

Figure 4. Received power to achieve FEC limit for different dispersive loads, exploiting maximum likelihood sequence estimation post-processing at 10 Gb/s. Labels clarifies the fiber type and the span length; NZD stands for negative non-zero DS fiber.

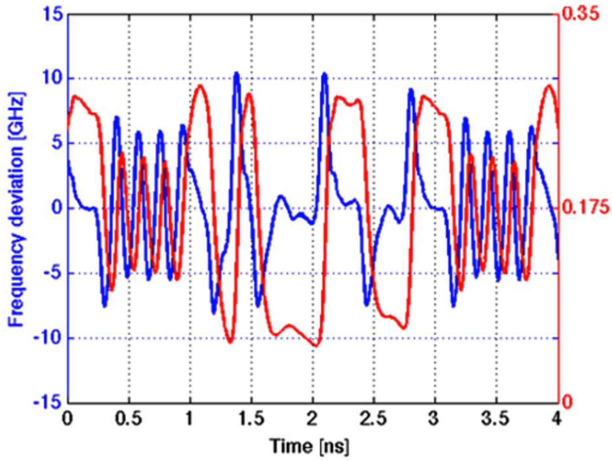

Figure 5. Measured frequency chirp (dark grey) and intensity (light grey) of the signal obtained by direct modulation at 10 Gb/s of the RSOA bias current.

3. Modeling of the CD Impact on the Self-Seeded Cavity

While measurements of the chirp, due to RSOA direct current modulation, certainly cover the issue of the propagation penalties in SSMFs at 10 Gb/s, by modeling the cavity operation, another aspect of the impact of CD on the 10-Gb/s performance is presented. The relatively long cavity of the RSOA-based self-seeded transmitter excites a large number of longitudinal modes. Such a multi-mode nature of the transmitter must be included in the mathematical modeling of the cavity to fully understand the impact of CD. Therefore, a multi-mode reflective SOA model that considers the signal and amplified spontaneous emission (ASE) fields was implemented based on [13, 14]. Then, it is combined with the AWG, which is modeled as a Gaussian optical bandpass filter (OBPF), and the optical fiber with CD and attenuation, as shown in the schematics of Figure 6.

To clearly see the role CD plays, CW operation of the RSOA-based self-seeded transmitter was simulated using a dispersive cavity with CD = 16 ps/(nm·km) and a dispersionless cavity with CD = 0 ps/(nm·km). Figure 7 shows the simulated signal

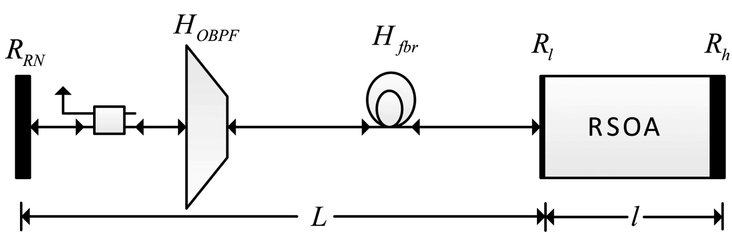

Figure 6. Schematic of the RSOA-based self-seeded transmitter. The cavity is formed between the RSOA mirror R_h and a second mirror R_{RN}. The gain medium is the RSOA with length l, while the cavity is the distribution fiber of length L and frequency response H_{fbr}. H_{OBPF} is the frequency response of the Gaussian-shaped OBPF.

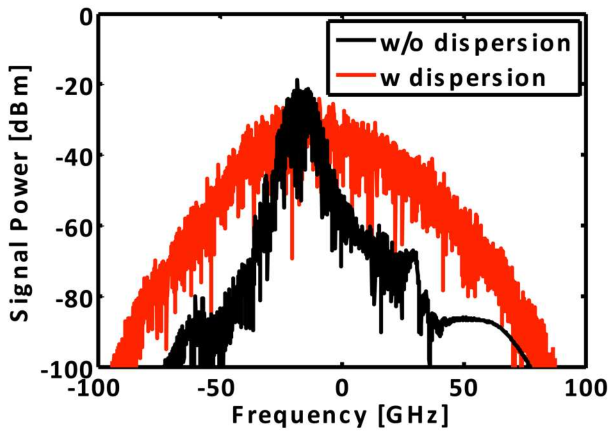

Figure 7. Plot of CW output signal of RSOA-based self-seeded transmitter with 5-km-long dispersive (CD = 16 ps/(nm·km) or dispersionless (CD = 0 ps/(nm·km)) cavities. The signal spectrum broadens due to the due to the accumulation of CD.

spectra for the two types of cavities having 5 km length. One can see that the dispersion causes significant spectral broadening, which will affect propagation performance. In addition, the CD will induce strong mode partition noise.

4. New O-Band RSOA Devices

New O-band RSOA chips have been fabricated with III-V buried ridge stripe technology from compressively strained InGaAsP multi-quantum wells (MQWs). With respect to previously designed and realized RSOAs operating in the C- band, some changes have been made to match the new operating wavelength band; in particular, the ridge width and spot-size converters design, as well as the barrier height, have been adapted. The actual O-band chips offer a high small-signal gain, above 25 dB at 1.32 μm and comparable with the gain displayed by the same devices designed for the C-band. As the PDG is very high, higher than 20 dB, again as for devices in the C-band, a two-FR setup is needed to control the signal SOP evolution when re-entering the RSOA. The RSOA spectra are centred around 1,320 nm and present gain ripples higher than 5 dB, as shown in the output spectrum recorded in Figure 8. Figure 9 displays the measured electro/optical response for one chip for various bias currents, which highlights the still limited bandwidth of this first generation O-band RSOA in comparison with C-band results. Furthermore, improved characteristics are expected from the InGaAlAs MQW, mainly because of the larger barrier height for electrons.

5. O-Band 10-Gb/s Operation

The experimental setup in Figure 3 has been exploited to compare the chips performance in C- and O-bands. Both setups in these two optical bands use the two-FR topology with Faraday elements operating in the respective spectral bandwidth. The cavity output couplers have a splitting ratio of 80/20 and 90/10, respectively, for C- and O-band operation,

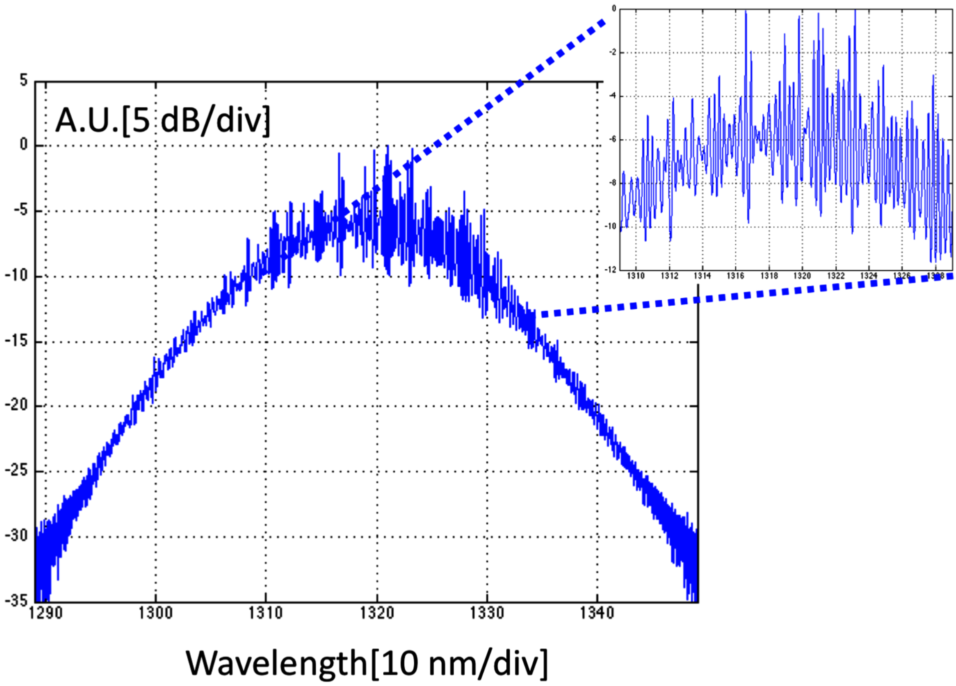

Figure 8. Output optical spectrum of the O-band RSOA centered at 1,320 nm; inset details gain ripples.

which is these best compromise between cavity losses and transmitter output power for the two cases. Bit-error ratio (BER) measurements at 10 Gb/s have been performed by an avalanche photodiode receiver followed by a commercially available clock and data recovery circuit with an electronic equalizer, namely a nine-tap feed-forward equalizer and a four-tap decision feedback equalizer.

Figure 10 shows the BER measurements obtained in the C-band for a 420-m-long cavity; diamonds relate to the transmitter with 220-GHz FWHM AWG, while circles

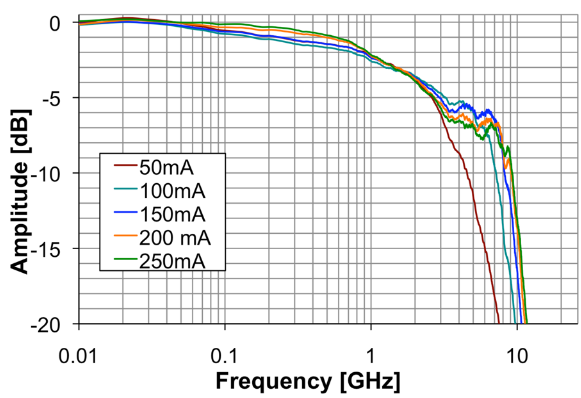

Figure 9. Electro-optical measurements at various wavelength for O-band RSOA.

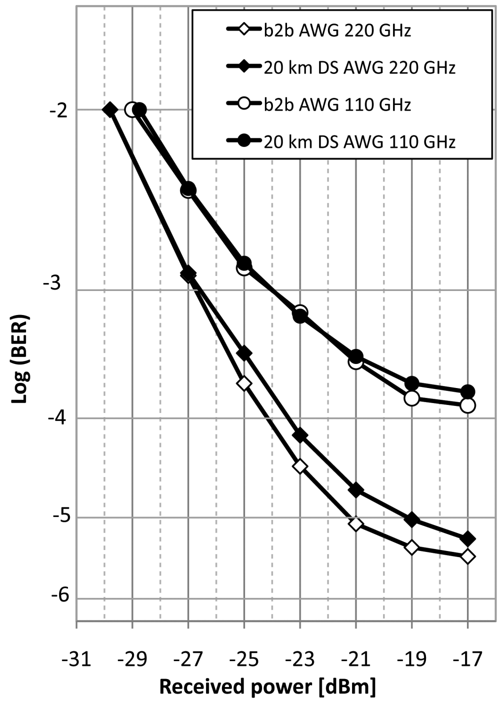

Figure 10. C-band 10-Gb/s BER curves in back-to-back (open symbols) and after 20 km of DS fiber (full symbols). Diamonds and circles curves refer, respectively, to the transmitter with 220-GHz FWHM AWG and 110-GHz FWHM AWG.

relate to the transmitter with a 110-GHz FWHM AWG. For the transmitter with a 220-GHz FWHM AWG, the back-to-back curves (open symbols) show an error floor below 10^{-5} BER, and negligible penalty is found after 20 km of propagation in a dispersion-shifted (DS) fiber (full symbols). For the transmitter with a 110-GHz AWG, both back-to-back and 20-km DS fiber curves present an error floor around 10^{-4} BER. It was previously pointed out that the propagation over the SSMF is limited to a few kilometers (see Figure 4). The proper comparison between O-band and C-band chips is to be performed with an equivalent amount of CD load, that is, for the C-band using a dispersion-shifted fiber. In particular, Figure 11a shows back-to-back performance when exploiting a 145-GHz FWHM optical tunable filter (OTF) with cavities of 420 m (squares) and 1 km (circles). The two curves show BER floors, respectively, below 10^{-9} and 10^{-7}. The O-band's better performance can be ascribed both to the absence of CD in the drop fiber, which influences cavity build up, and the very low cavity roundtrip losses associated to the OTF based cavity, which are 6 dB lower with respect to the C-band AWG cavity, and which allow for better relative intensity noise suppression and higher output extinction ratio [15]. Figure 11b shows the performance of the cavity with a 20-m drop fiber back to back (squares) after propagation in 20-km SSMFs (circles) and in 52-km SSMFs (triangles). As expected, no CD penalties can be found, confirming that the O-band choice permits the bridging of feeder fibers as long as allowed by the back-to-back performance and cavity output power.

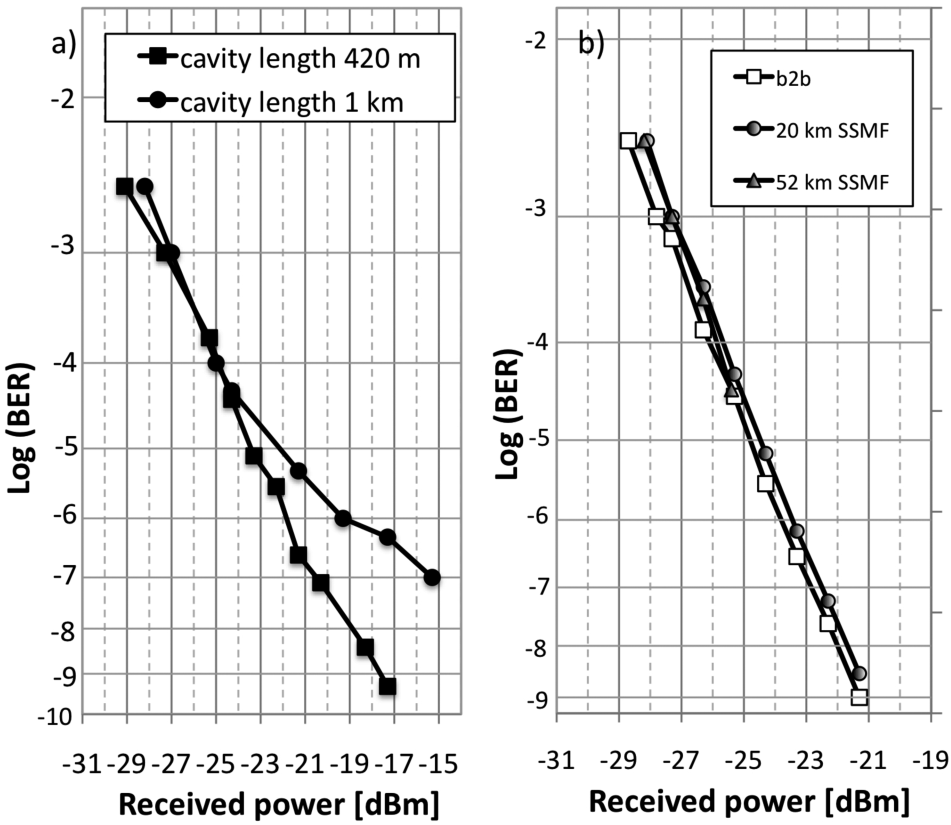

Figure 11. Ten-Gb/s BER curves: (a) back-to-back with 420-m drop fiber (squares) and 1-km drop fiber (circles), (b) 20-m drop fiber back-to-back (open squares) after 20-km SSMFs (circles) and after 52-km SSMFs (triangles).

6. Conclusions

WDM PON architectures are increasingly finding new applications in the optical access. Point-to-point WDM PONs connectivity provides a high wavelength channel capacity that is appealing, for instance, for mobile applications, as discussed in Section 1. Colorless WDM PON solutions suppress inventory issues, and when relying on self-seeded optical sources, their advantages increase, as they automatically and passively assign the wavelength to the ONU without any external control. This work aimed at focusing on the self-seeded topology, illustrating issues related to the 10-Gb/s target with particular regard to the impact of CD. Experimental results in fact demonstrated that in propagation, a clear asymmetry concerning the capability to deal with CD load is present at 10 Gb/s. It was shown though experimental measurements that this asymmetry is due to the chirp associated to RSOA direct modulation. Additionally the theoretical analysis operated by means of a mathematical modeling of the cavity; taking into account the multi-mode nature of the transmitter showed that not only the feeder fiber CD impact on the performance of the transmitter but also the length and CD of the drop fiber, which constitutes the cavity, cause a broadening of the transmitter optical spectrum. This issue is of no minor importance, as it may limit the applications of the self-seeded topology.

In this work, after the analysis of the issue, a possible solution allowing for ODN fiber plant reuse was presented. By exploiting the AWG cyclic transfer function, suitable RSOA chips are needed in the O band, which have been designed and realized by the III-V Lab. Final characterization not only demonstrated very good performance at 10 Gb/s; also, by comparing the O-band chips with that previously developed in C-band under similar CD loads, it was demonstrated that the new chips perform equivalently while solving the CD issue and allowing for SSMF infrastructure reuse.

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