Dense SS-WDM Over Legacy PONs: Smooth Upgrade of Existing FTTH Networks

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***Abstract*—We propose a hybrid passive optical network (PON) architecture supporting time-division multiplexing (TDM) and dense spectrum-sliced wavelength-division multiplexing (SS-WDM) over the legacy PON infrastructure. We use a fiber Bragg grating (FBG)-based self-seeded reflective semiconductor optical amplifier (RSOA) transmitter in conjunction with a recently proposed balanced receiver (BR); identical transceiver pairs are placed at the central office and customer side. Self-seeded RSOAs obviate the need for centralized sources, providing a high power, directly modulated source. Intensity noise mitigation of this thermal source is investigated by operating the RSOA in saturation and employing the recently proposed BR. We study the optimal reflectivity for seeding that balances signal power and noise cleaning to achieve the best bit error rate (BER) possible; channel widths are comparable with dense WDM when using coherent sources.**

We experimentally demonstrate a symmetrical 1.25 Gb/s dense SS-WDM transmission over the legacy PON infrastructure using our optimized self-seeded RSOA transmitter and the BR. Using a reflective $(18 \pm 2\%)$ FBG for self-seeding, we achieve up to 4.5 dBm of output power within a 25 GHz channel. Error free transmission $(\mathrm{BER} < 10^{-10})$ is achieved over a 20 km feeder. We investigate the possibility of colorless ONU operation. The power budget allows 32 users (64 users with reasonable OLT amplification) to be supported over the existing PON infrastructure. Simulations show capacity increases to 128 users when a Reed–Solomon RS(255, 239) forward error correcting code is used.

***Index Terms*—Balanced detection, fiber Bragg gratings (FBGs), fiber-to-the-home (FTTH), noise cleaning, passive optical networks (PONs), remodulation, self-seeding, semiconductor optical amplifiers (SOAs), spectrum-sliced wavelength-division multiplexing (SS-WDM).**

I. Introduction

DENSE spectrum-sliced wavelength-division multiplexing (SS-WDM) is an attractive solution for increasing the capacity of future fiber-to-the-home (FTTH) access networks. Such systems benefit from the same advantages as WDM, while employing low cost incoherent light sources [1]. Currently, the capacity of existing FTTH passive optical networks (PONs) is under 100 Mb/s per client, as users share the aggregate bit rate using time-division multiplexing (TDM) [2]. Bandwidth hungry applications such as broadband Internet access, high-speed file transfer, remote storage, video services with high-definition TV quality, high-quality online multi-party video gaming, etc, are driving the service providers to migrate from standard TDM-based PONs to high capacity future PONs [3], [4] with symmetric up and down stream bandwidths [5], and increased bit rate per user.

WDM increases the capacity of legacy PONs by assigning different wavelengths for different optical network units (ONUs), i.e., different subscribers [6]. However, deploying WDM in existing PONs requires in most cases that the existing passive splitters at the remote nodes (RNs) be replaced with arrayed waveguide gratings (AWGs), as well as upgrading ***all*** optical line terminal (OLT) equipment and ONUs. OLT and ONU upgrades can be made on a per subscriber basis for our hybrid TDM/WDM solution allowing a gradual rollout of high bit rate clients [6]. The use of reflective semiconductor optical amplifiers (RSOAs) as incoherent sources lowers cost, but they suffer from severe intensity noise, forcing a tradeoff between the spectral efficiency and the bit rate [7].

A. Related Work

There are two separate research areas regarding WDM PONs that exploit RSOAs that are relevant to this work. One addresses the use of self-seeded RSOAs as ONU light sources, the other studies semiconductor optical amplifiers (SOAs) as noise cleaning devices. In this subsection we give a brief overview of this related work, and in the next subsection we outline our novel combination of these two separate and distinct research thrusts.

RSOAs have been widely proposed as inexpensive wavelength independent or 'colorless' ONU transmitters in WDM and SS-WDM PONs using centralized light sources [8], [9]. Given that the RSOAs can serve as incoherent light sources, researches have examined the possibility of eliminating the centralized source. In other words, instead of amplifying/modulating a signal originating at the central office, the RSOA modulates its own thermal emissions. To concentrate all available light into a particular WDM waveband, and thus to increase power, RSOAs can be self-seeded [10]–[13]. In such systems, the passive filtering device at the RN concentrates the ASE emission of the RSOA into one band, feeding back the light in that band only to the RSOA. The RSOA continues to amplify

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this band until no ASE appears outside the band. Please note that such systems require that the legacy PON infrastructure be upgraded to AWGs at the RN.

When using a thermal source for spectrum sliced WDM, intensity noise limits overall performance and incurs error floors. A rich body of research has examined the use of the nonlinear dynamics of SOAs to mitigate this intensity noise [14]. When no channel selection filter is used, the so called degenerate case for WDM, the noise suppression is remarkable. Unfortunately receiver side filtering using a conventional channel select filter finds the intensity noise returning in force. Typically wide filtering at the receiver can find a compromise between spectral efficiency and noise cleaning. Recently, Mathlouthi, *et al.*, [15] proposed a balanced receiver (BR) for dense SS-WDM systems that preserves significant noise cleaning so that dense WDM channel spacing can be achieved even with thermal sources.

B. Our Contribution

Previous studies used in-line SOAs to suppress the intensity noise of a separate thermal source, and did not involve the use of RSOAs in a combined role of thermal source and noise mitigation device. We confirmed that a self-seeded RSOA signal exhibits a significant reduction in intensity noise, comparable to centralized thermal sources that are amplified by the RSOA. We investigated the use of the recently proposed balanced receiver and confirmed that noise mitigation is preserved in the case of self-seeded RSOAs, as has been observed with in-line SOAs. In this paper we report on two aspects of the combination of self-seeding with balanced detection: 1) the optimization of spectral efficiency, and 2) the architectural impact for PONs.

We propose a self-seeded transmitter that uses a partially reflective ($p\%$) fiber Bragg grating (FBG) directly following the RSOA. Optimizing power output for self-seeding requires that some light be shunted to seeding, while the balance of light exit the FBG as the output signal. Optimizing noise cleaning requires that the SOA or RSOA operate in deep saturation. High FBG reflectivity guarantees that the RSOA is deeply saturated, thus improving noise suppression, although decreasing output power. Lower FBG reflectivity increases output power, but reduces noise suppression. We optimize the FBG reflectivity to balance these effects and minimize the bit error rate (BER).

The BER is a function not only of the FBG reflectivity, but also the filtering strategy used at the receiver. We consider three strategies: the degenerate[1] receiver (DR) without a channel select filter (CSF), the conventional receiver (CR) with a CSF, and the balanced receiver (BR) from [15] employing a notched filter in one receiver arm to achieve channel selection. We show experimentally that when using a self-seeded RSOA as a source, the BR outperforms the CR, and indeed, the BR performance approaches the DR performance. These results confirm that noise mitigation is preserved in the RSOA/BR architecture.

Our use of a $p\%$ reflective FBG for self-seeding contrasts with [10]–[13] where a totally reflective grating and 1×2 coupler combine to achieve 50% effective reflectivity. No attempt was made in those studies to examine the noise mitigation, and therefore no optimization of the reflectivity.

Our combination of self-seeded RSOA transmitter (Tx) with partial notch filtering at the receiver (Rx) has an interesting impact on the PON architecture. The use of passive filtering in the RN would essentially imply "receiver side" filtering that would negate the noise cleaning advantages, unless that filtering was extremely wide (very spectrally inefficient). The combined RSOA/BR strategy is therefore best targeted as an innovative method for gradually upgrading existing PONs from TDM to SS-WDM with no modification to the passive splitter RN. Legacy users remain on the main PON wavelength band, while SS-WDM users could be placed in another band or in the enhancement band (when not used for video).

The RSOA/BR combination offers tight wavelength packing (dense WDM), and therefore a viable means of rolling out a large number of higher paying, higher performance clients, without incurring the expense of upgrading the RN to stabilized AWGs, and upgrading all ONUs. The RSOA also affords a less expensive, more compact, and more powerful transmitter, compared to the traditional SS-WDM transmitter in [15]. We examine as well the possibility of remote self-seeding when placing the FBGs at the RN, to reduce ONU cost.

C. Multi-Channel Operation

The reader will note that all experimental results presented are for single user systems and no examination is made of system crosstalk. The spectral efficiency of our solution is implied by the ratio of bit rate and width of the FBG slicing filter. All single user systems assume a channel select filter that is the same bandwidth as the slicing filter. We examine dense WDM spacing ($\sim$30 GHz) and bit rates of 1.25 Gb/s

Cross-talk is an important factor when using wide filtering at the receiver to maintain noise cleaning. Depending on the channel width chosen the cross-talk or intensity noise could be the dominant noise source. When using balanced detection, however, the cross-talk was shown to have no discernable impact on performance [15]. Given the lack of equipment for multi-channel operation, and the previously demonstrated robustness of BR to cross-talk, we focused our attention on the single channel experimental validation. Our contribution is finding the optimum balance of output power versus noise mitigation via the $p\%$ factor.

While cross-talk is negligible in this study, the use of a multi-channel system will invoke significant splitting losses. We use our single channel measurements to analyze the power budget in multi-channel systems. We investigate the capacity of our proposed system both spectrally as well as via power budget.

The rest of this paper is organized as follows. In Section II we discuss the impact on PON architecture when using self-seeded RSOA transmitters. We focus on our proposed transmitter and discuss the challenges in combining noise cleaning with self-seeding and the optimization of the FBG reflectivity. In Section III we present how TDM PONs can be migrated to dense SS-WDM PONs. Our experimental results are presented and discussed in details in Section IV. Technological and architectural considerations are highlighted in Section V, as are performance and cost issues. A demonstration of remote

[1]This receiver has ideal noise cleaning, but is incompatible with WDM as there is no channel selection, hence the name degenerate.

self-seeding and a discussion of other requirements for colorless ONUs appears in Section VI. We summarize and conclude in Section VII.

II. Self-Seeded RSOAs: Impact on PON Architecture

The availability of inexpensive RSOAs is enabling next generation multiple wavelength PONs. The direct slicing (filtering) of the RSOA amplified spontaneous emission (ASE) for SS-WDM systems is impractical as it is not power efficient. Therefore, a centralized light source (placed at the OLT) is distributed to the ONU [8], [9], and [15]–[18]. RSOAs at the ONU directly modulate the distributed source for the uplink, thus providing amplification while avoiding external modulators. In this configuration, the ONU transmitter is not wavelength-specific, hence relaxing the wavelength management on the customer side of the access network [9]. If the RSOA is operated in saturation it can also provide noise cleaning of the incoherent source, via the same mechanisms as do semiconductor optical amplifiers (SOAs) [16].

Several architectures exist for centralized sources. One solution uses a centralized continuous wave (CW) broadband, incoherent source at the OLT; the light is sliced by the AWGs at the RN and injected to an RSOA (or SOA) for uplink modulation. Another solution uses re-modulation techniques, injecting the RSOA with a low extinction ratio (ER) downlink signal to be re-modulated with higher ER upstream data to "recycle" the downstream data signal [17], [18]. Remotely pumped erbium-doped fiber amplifiers (EDFAs) have also been proposed to enhance the performance of RSOA-based hybrid WDM PONs, where a pump laser is located at the OLT and only erbium-doped fibers deployed near the RN [19].

In the following we discuss how self-seeding of RSOAs can obviate the need for a centralized source. Power levels are high, and noise cleaning will be exploited to a great degree by use of a recently proposed receiver. The combination of these novel transmitters and receivers will enable dense channel spacing even with thermal (RSOA) sources. Most importantly, these upgrades can be achieved over the installed PON infrastructure as seen in Section III. The cost of these advantages is creating wavelength dependent ONUs; possible extensions to colorless operation will be examined in Section VI.

A. Proposed Self-Seeded RSOA-Based Transmitter

Recently, self-seeded RSOA-based ONU transmitters were proposed [10]–[13] whose launch power is sufficient to eliminate the need of a centralized light source at the OLT and remotely pumped EDFAs. In [11] remote self-seeding was proposed using a reflective filter at the AWG-based RN, however an EDFA was required at the RN (making the network no longer passive) to overcome round trip losses and to ensure sufficient power is re-injected to the RSOA. To overcome such problems, local self-seeded RSOA transmitters were proposed in [12] and [13] where a 100% reflective FBG placed at the ONU is used for self-seeding.

Our first goal is to confirm self-seeded operation of the RSOA using a commercially available optical filter (the tunable 30 GHz wide TB9 grating filter from JDS Uniphase in the upper setup of

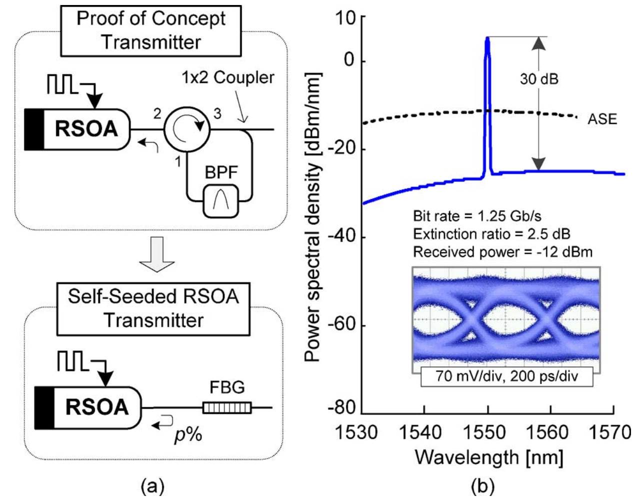

Fig. 1. (a) Proposed self-seeded RSOA transmitter using a reflective FBG as well as an alternate configuration for proof of concept. (b) Power spectral density for a 55 GHz channel at 1550 nm.

Fig. 1(a)). Next we will examine optimization of the FBG reflectivity ($p\%$) at the ONU as shown in the lower setup of Fig. 1(a). Instead of maximizing launched power as was done in the past, we will optimize bit error rate. Due to the nonlinear interaction in the RSOA (see the next subsection on noise cleaning), maximizing the launched power does not minimizes the BER when using a receiver designed to exploit noise cleaning to its fullest potential.

The RSOA is self-seeded with a filtered version of its ASE, while directly modulating its current with a low extinction ratio (ER) to favor erasure and remodulation inside the feedback loop [17], [18]. Clearly high ER facilitates detection; therefore there exists an optimum ER that permits both remodulation and reliable detection. We employ a non-return to zero (NRZ) 2^7-1 pseudo random binary sequence (PRBS), in order to have a signal similar to the 8 B/10 B encoding of Gigabit Ethernet [17]. We found experimentally that a bias of 3.5 V and a 2 V peak-to-peak variation gave no apparent jitter and provided the correct tradeoff on the ER. Using a 50/50 coupler and under these biasing conditions, the re-injected power was -4 dBm enough for saturating the RSOA we used (SOA-R-OEC-1550 from CIP).

The power spectral density (PSD) at the output of our proof of concept transmitter is plotted in Fig. 1(b) when the TB9 filter is tuned to 1550 nm. The spectrum is enlarged after passing through the RSOA so that the 3 dB bandwidth is now 55 GHz. The output ASE from the RSOA before the 1×2 coupler is also plotted for comparison; the total ASE power at that point was 4 dBm. The transmitter provides 30 dB of out of band ASE suppression and 1 dBm of output power. Traditional slicing of the RSOA ASE (not shown), yields out of band ASE suppression of 38 dB and output power of -21 dBm. Self-seeding concentrates the ASE power of the RSOA into a specific band increasing the in-band power, i.e., the power efficiency.

A back-to-back eye diagram at 1.25 Gb/s and -12 dBm of photo-detected power is shown as an inset of Fig. 1(b), when no CSF is used before detection, i.e., for the DR. The clean eye is due to both the saturation effects in the RSOA that leads to noise

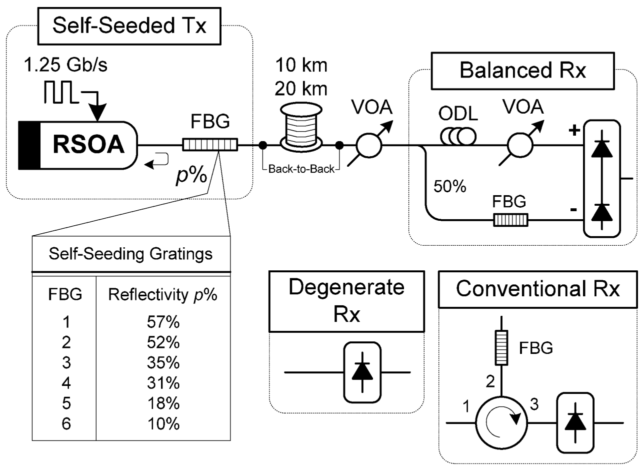

Fig. 2. Experimental setup showing our self-seeded RSOA transmitter with the three receiver structures under test and a table with the FBGs used for self-seeding (ODL: optical delay line, VOA: variable optical attenuator).

cleaning of incoherent light, and the use of the DR that preserves noise cleaning (by obviating optical filtering). Completely uncorrelated light becomes partially correlated, imparting noise cleaning effects. Not only are self-seeded RSOA outputs greater power, they also have low intensity noise. Unfortunately much of the noise cleaning effect is lost when using a channel select filter [16], [20], such as the typical use of an AWG in the RN.

B. Noise Cleaning in SS-WDM Using a Balanced Receiver

In order for the noise cleaning to carry through to reception, optical filtering should be avoided as reported in [20]. Recently, Mathlouthi, *et al.*, proposed and demonstrated a balanced receiver for SS-WDM systems that preserves much of the noise cleaning achieved by semiconductor optical amplifiers even in dense WDM channel spacing [15]. The upper arm of this receiver is an all-pass filter and the lower arm is a notch filter centered on the desired channel, as shown in part in Fig. 2. An FBG operating in transmission serves as a notch filter; the coupling ratio of the 1×2 coupler is carefully selected to ensure balancing thus reducing channel cross-talk. The bandwidth of the notch filter is designed to be larger than that of the self-seeding FBG to allow a certain detuning between the transmitter and receiver due to possible temperature variations at the ONU side. While two photodetectors are used in this solution, the cost of the receiver is not significantly higher than that of standard SS-WDM systems.

Recall that filtering a noise-cleaned signal deteriorates its performance. If the channel select filter (CSF) bandwidth is wide enough compared to the WDM slice width, the performance can still be acceptable [16], [20], however the channel spacing will be high, reducing the spectral efficiency. Dense SS-WDM using self-seeded RSOA transmitters can be efficiently achieved using instead the BR. In our proposal the FBG used at the transmitter is less than 20% reflective (as will be seen in Section IV.C), therefore it is not a classical filter; the post-filtering effect was observed for a single pass through a filter with 100% transmissivity. In our case the dynamics are much more complex. The filter is building up the output signal using feedback, working with the RSOA dynamics to achieve (not destroy) noise cleaning. Passive post filtering after our FBG does destroy this self-seeded noise cleaning as it does in other systems using SOAs for intensity noise cleaning.

Note that previous demonstrations of this recently proposed balanced receiver for noise cleaning used SOAs and external modulation. Our proposal is the first examination and optimization, to our knowledge, of noise cleaning on a self-seeded RSOA. Our RSOA-based transmitter greatly reduces the complexity and cost over the architecture in [15] as the RSOA performs modulation, amplification and noise cleaning at the same time.

An FBG with partial reflectivity is the key to minimizing the bit error rate by trading off noise cleaning versus transmitter output power. For optimal noise cleaning, the RSOA should be deeply saturated requiring a certain amount of power be fed-back to the RSOA, and therefore affecting the output power. Therefore, we fix the channel (slice) width of the FBG in Fig. 1(a), and vary reflectivity (values are shown in Fig. 2) to achieve various levels of saturation. Reflectivity greater than the optimum decreases the output power, without sufficiently enhancing the noise cleaning. Based on our original experimentation with the JDS tunable filter (and knowing the transmitter output power and the RSOA seed power), we set the FBG bandwidth to 37.5 ± 2.5 GHz, and fabricated six chirped FBGs with reflectivities ranging from 57% to 10%; the group delay response was controlled to avoid dispersion-like problems. In Section IV we find the optimal reflectivity experimentally. To implement the BR adapted to our choice of self-seeding FBG, we fabricate a 100 GHz wide FBG to serve as a notch filter for the BR and a CSF for the CR when operated in transmission and in reflection, respectively.

III. Dense SS-WDM Over Existing PONs

In this section we take the opportunity to discuss how the transmitter and receiver pair we propose can be exploited over the existing PON infrastructure. Typically, a PON has a physical tree topology with the OLT located at the root and the subscribers connected to the leaf nodes of the tree through a passive coupler, as depicted in the shaded portion of Fig. 3. Existing PONs are TDM-based; a single transceiver is located at the OLT and serves N legacy ONUs. A coarse WDM (CWDM) filter is used at both terminals to separate the upstream (1310 nm) and downstream (1490 nm) traffic) [2]. The 1550 nm band is normally reserved for video distribution in the PON standards. While the PON standards specify a maximum feeder length of 20 km and a maximum split ratio of 1:64 for gigabit PON (GPON), in practice the maximum reach of 20 km and a PON split of 1:32 cannot be achieved simultaneously [21].

Fig. 3 shows also the necessary upgrades at the OLT and ONUs to support dense SS-WDM in the 1550 nm band within the legacy passive splitter-based infrastructure. At the central office a coupler similar to the one already installed at the RN is added, and a bidirectional erbium-doped fiber amplifier (BEDFA) is used to compensate for the added coupling losses. The coupler and the BEDFA can be easily integrated into a lossless coupler using an erbium-doped waveguide amplifier.

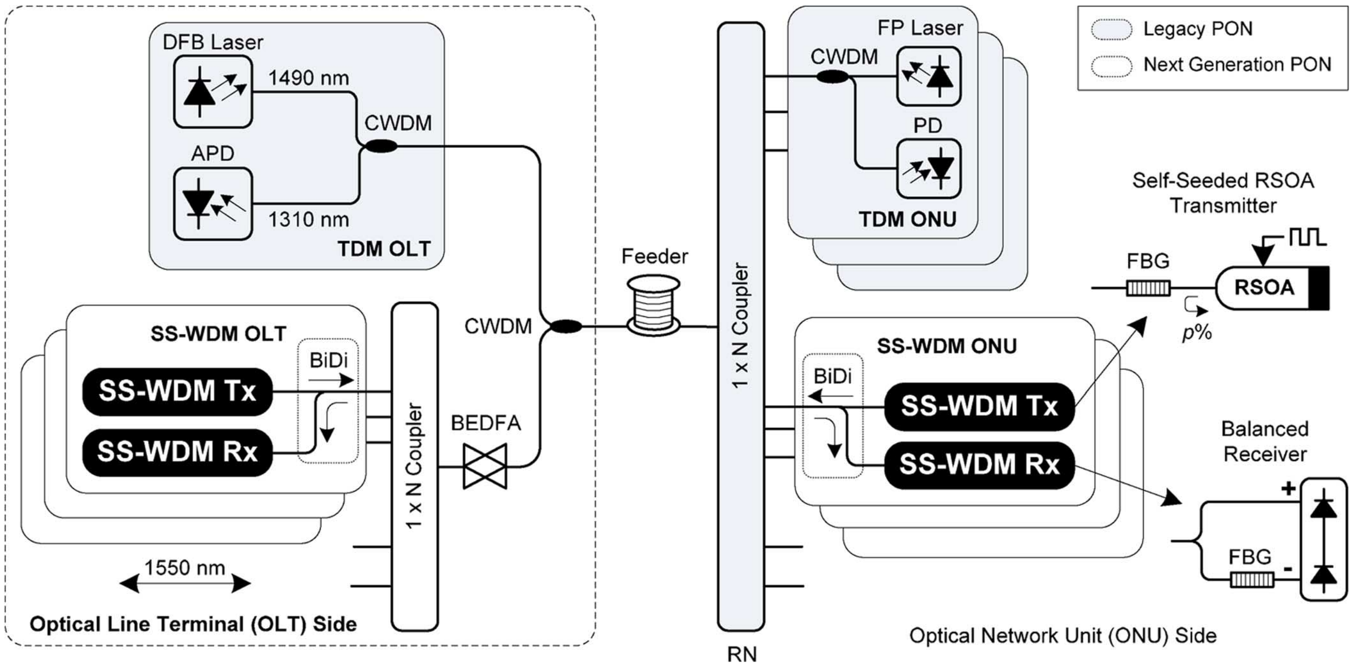

Fig. 3. Hybrid dense SS-WDM PON and TDM PON over the existing PON infrastructure (APD: avalanche photodiode, BEDFA: bidirectional EDFA, BiDi: bidirectional, CDWM: coarse WDM, DFB: distributed feed-back, FBG: fiber Bragg grating, FP: Fabry-Perot, PD: photodiode, Rx: receiver, Tx: transmitter).

CWDM filters are used at the OLT to separate the three wavebands. Bidirectional (BiDi) modules (also called wavelength couplers) are used to separate uplink and downlink.

Identical dense SS-WDM transceiver pairs are used from both network sides for new clients that will exploit the high data rates achievable by introducing multiple wavelengths. Each transceiver is equipped with a self-seeded RSOA-based transmitter identical to the one in Fig. 1(a), and the BR [15] seen in Fig. 3. Subcarrier multiplexing (SCM) can be used to separate the uplink and downlink traffic for full duplex communication when the same wavelength is used in both directions [22]. The architecture is flexible enough to allow other techniques to be used for full duplex operation. The entire C-band can be exploited due to the availability of RSOAs with bandwidths as large as 40 nm.

Currently, the modulation speed of RSOAs is limited up to 2.5 Gb/s by current technologies, which is sufficient for FTTH access networks. For field deployments, polarization independent RSOAs in TO-CAN packaging are commercially available at very competitive pricing (already in small quantities the cost is a few hundred dollars), making our solution a potentially cost-effective upgrade for existing PONs. Compared to traditional SS-WDM PONs, our architecture offers reduced PON capital expenses (CAPEX) as it exploits current generation equipment, and mature inexpensive splitters. Challenges remains for splitting loss in scaling the network (compared to AWG-based PONs) and is discussed in Section V. The possibility of colorless ONU operation is discussed in Section VI.

IV. Experimental Results and Discussions

In this section, we experimentally study the performance of our proposed self-seeded RSOA transmitter with the BR as well as the CR and DR. We find the optimum value of the reflectivity of the self-seeding FBG in order to benefit from both self-seeding and noise cleaning.

The DR enjoys all noise cleaning advantages, while the BR does better than other filtering scheme, but still suffers from reduced noise cleaning, even in the single user case. An important conclusion from [15] is that the BR does not experience any further performance loss when adjacent channels are present, i.e., loss in noise cleaning dominates the performance, not adjacent channel crosstalk. For this reason we confine our experimentation to the single user case. Note that per [15], the crosstalk penalty (7 channels) was negligible even at 10 Gb/s for 30 GHz channels spaced by 100 GHz (our tested channel allocation).

As the RSOA is deeply saturated (to benefit from noise cleaning), it acts as a high pass filter and reduces the effect of Rayleigh backscattering, reflection interferences, and ASE. Therefore, the effect of Rayleigh backscattering and such in-band crosstalk is negligible.

A. Experimental Setup and FBG Characterization

Fig. 2 shows the experimental setup used to evaluate the optimum value of the reflectivity of the self-seeding FBG. In addition to the BR, the DR and CR are examined as a reference. The RSOA is directly modulated at 1.25 Gb/s with an NRZ $2^7 - 1$ PRBS. The bias is kept at 3.5 V and the signal peak-to-peak variation at 2 V for optimum data erasure and remodulation; RSOA temperature is maintained at 20°C.

At the transmitter side we use our proposed self-seeded RSOA transmitter with six different FBGs as listed in inset table of Fig. 2. Standard single mode fiber (SMF-28) of 10 or 20 km is used to represent the PON feeder; no dispersion compensation is used. Since the RN contributes only to splitting losses, we forgo a $1 \times N$ coupler; in Section V, we calculate power budget and maximum supported splitting ratio.

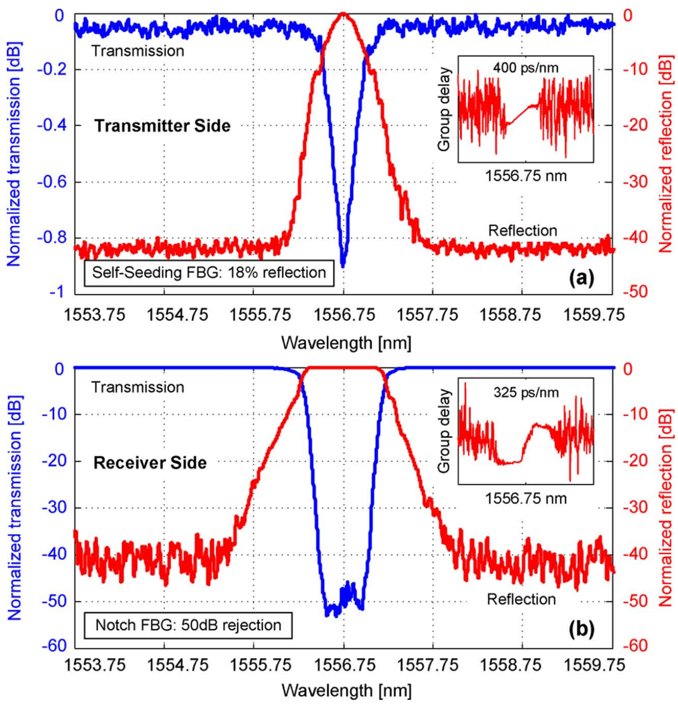

Fig. 4. Characterization of the 18% self-seeding FBG used at the transmitter and the FBG used with both the BR and the CR.

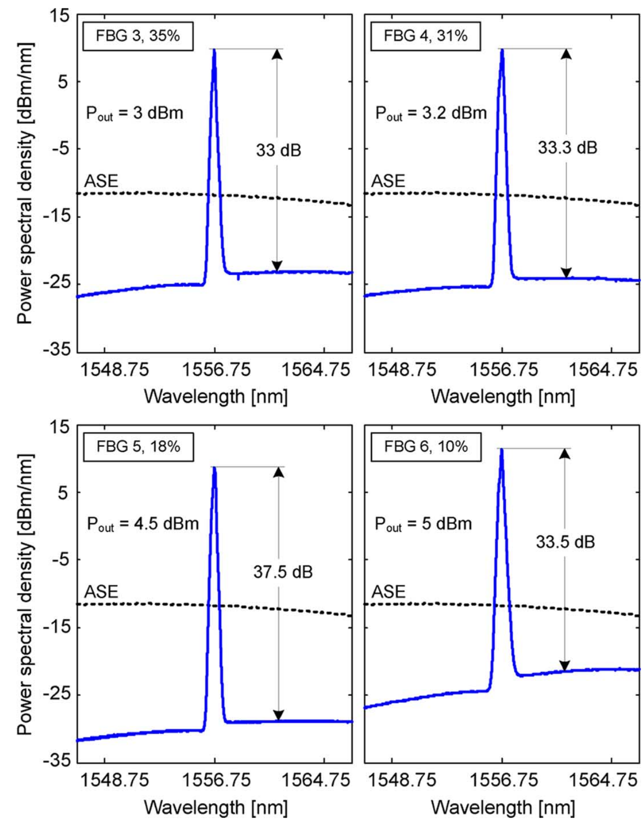

Fig. 5. Power spectral density at the output of our proposed self-seeded RSOA transmitter for FBGs with 35%, 31%, 18%, and 10% reflectivities, compared to the output ASE from the RSOA without self-seeding.

At the receiver side a variable optical attenuator (VOA) is used to control the received power for the BER measurements. For the BR a 3 dB coupler is used as in [15]; at the lower arm a notch filter implemented using an FBG working in transmission is used. A variable optical delay line (ODL) is used in the upper arm and is adjusted to maintain good synchronization between the signals at both arms. Another VOA minimizes cross-talk by assuring that the out of band signals (including ASE) are exactly canceled by balanced detection.

The DR is simply a photodiode (PD) without any CSF, whereas the CR uses a circulator and the same notch filter FBG as the BR, but now operated in reflection as a CSF. An 800 MHz balanced PD from New Focus is used for all three receiver types. The PD is followed by an RF amplifier (JDS H301-2310) and a 4th order 933 MHz Bessel-Thomson low-pass filter (LPF) to suppress out of band noise.

All FBGs are mounted on stretchers and their wavelength is tuned to 1556.75 nm with ± 0.05 nm precision. In Fig. 4 we plot the normalized transmission and reflection response of the 18% reflective self-seeding FBG (Fig. 4(a)) as well as the notch filter FBG (Fig. 4). All the gratings were designed having a Gaussian profile in reflection. The self-seeding FBG 5 is exactly 35 GHz wide in reflection, whereas the notch filter FBG is 100 GHz wide in reflection and has 50 dB of rejection. The group delay responses of both FBGs are shown in the insets.

The 100 GHz wide FBG at the receiver is considered as a wide CR and does not degrade the performance considerably compared to a CR with a CSF having a bandwidth equal to that of the SS-WDM channel [15], [20]. This represents the best compromise of spectral efficiency and noise cleaning for a standard channel select filter, i.e., optimal bandwidth. This identical width is used for the BR notch filter. While this leads to some compromise on spectral efficiency, the BR will still see much better noise cleaning than the CR. The relatively wide channel spacing allows for a certain wavelength drift due to possible temperature variations when the FBGs at the ONUs are not packaged using a temperature compensating package [23], especially when the ONUs are located outdoor.

B. Characterization of the Proposed Transmitter

All six FBGs listed in Fig. 2 were tested, however, we only present results for FBG 3, FBG 4, FBG 5, and FBG 6 as FBG 1 and FBG 2 have reflectivities far from the optimum. The output PSDs (exiting the self-seeded transmitter) are plotted in Fig. 5. Judging strictly by output power, decreasing the reflectivity of the FBG from 35% to 10% increases the output power from 3 dBm to 5 dBm. The output ASE from the RSOA without self-seeding is also plotted in dotted lines. FBG 5 $(p = 18\%)$ gives the optimum performance in terms of the out of band ASE rejection; the optical signal-to-noise ratio (OSNR) is increased by 4 dB as compared with FBG 6, while output power is only decreased by 0.5 dB, less output power than FBG 6. The seed power for FBG 5 is -6 dBm, enough to saturate the RSOA and improve noise cleaning. Note the output frequency band and 3-dB bandwidth of 25 GHz due to the transmission response (Fig. 4) of the FBGs. In the case of the JDS filter implementation, the filter transmission response is flat over all wavelengths leading to bandwidth expansion due to nonlinear effects in the RSOA.

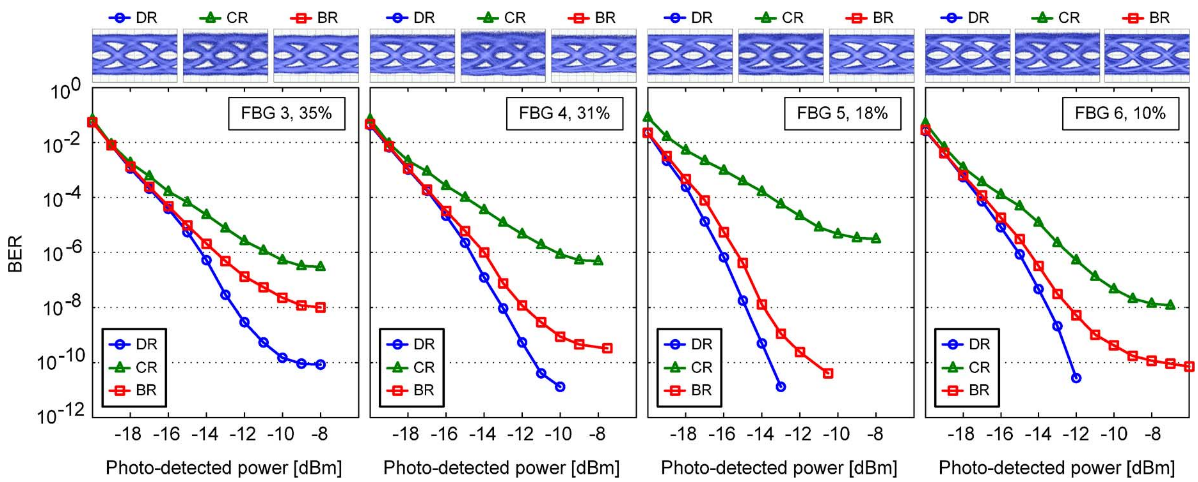

Fig. 6. Back-to-back BER performance corresponding to the same FBGs in Fig. 5 when using the three receiver options (BR: balanced receiver, CR: conventional receiver, DR: degenerate receiver).

C. Optimization of the BER Performance

Ultimately we wish to optimize bit error rate performance rather than output power or output OSNR. We conduct back-to-back transmission experiments for each reflectivity and measure bit error rates for each of the three receivers under evaluation, reported in Fig. 6. The horizontal axis represents the photo-detected power, i.e., the power at the PD and not at the receiver input. The degenerate receiver (no receiver side filtering, circle markers) shows the best performance and serves as a benchmark. FBG 5 at 18% gives the best performance among the reflectivities tested. The same trend can be observed for the set of curves for the BR (square markers) with the optimum performance for 18% reflectivity. This demonstrates the tradeoff between noise cleaning and self-seeding already discussed. As the CR (triangle markers) suffers a significant loss in noise cleaning advantage [20], the trade-off between crosstalk and noise cleaning is different for this receiver, with a minimum for FBG 6 ($p = 10\%$). The BR outperforms the CR as already demonstrated in [15] and approaches the performance of the DR for optimal FBG reflectivity. Eye diagrams at -12 dBm are also provided.

Having established an optimum reflectivity exists between 31% and 10%, we next examine the sensitivity of the optimality in the neighborhood of 18%. We fabricated two additional FBGs with 13% and 23% reflectivities and tested them with the BR. In Fig. 7 we plot the sensitivity versus the FBG reflectivity at BER 10^{-9} and 10^{-10}. The back-to-back BER measurements as well as the corresponding eye diagrams at -12 dBm photo-detected power are shown as an inset. We conclude that the optimum reflectivity would be 18%±2%. This optimum is not unique; it depends on the characteristics of the RSOA and the channel 3 dB bandwidth. The key idea is to get the good amount of seed power that optimizes the self-seeding and noise cleaning simultaneously. Note that while our results based on both OSNR and BER optimality coincided in this experiment (both were maximized by FBG 5 at 18%) this is not always the case as noise statistics for noise cleaning are in general highly non-Gaussian [15].

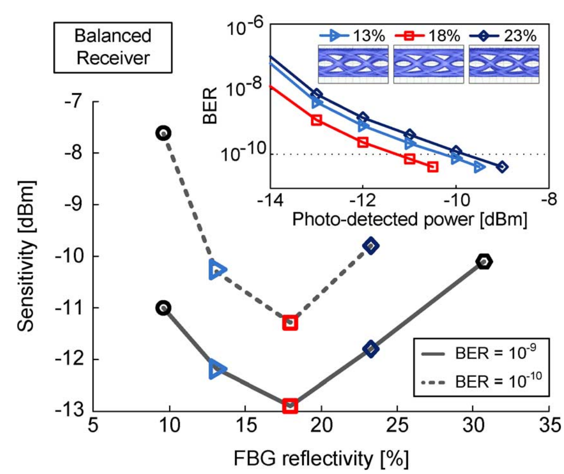

Fig. 7. Sensitivity versus FBG reflectivity for the BR.

D. Uplink/Downlink Transmission

We next move from back-to-back to propagation experiments using FBG 5. The self-seeded RSOA transmitter is modulated at 1.25 Gb/s across symmetrical 10 km and 20 km PON links, with the BR at the receiver side, per Fig. 2. The BER performance is shown in Fig. 8, where we plot the BER measurements (unfilled markers) for a 10 km (circle markers) and a 20 km (square markers) feeder. A dispersion penalty of 2.3 dB is discernable for the 10 km case when comparing with back-to-back measurements; at 20 km the penalty is an additional 3 dB due to additional fiber attenuation and dispersion. Error free (BER below 10^{-10}) performance is achieved for both feeder lengths. Eye diagrams at -12 dBm are shown as an inset. We also plot simulations (filled markers) of forward error correction (FEC) performance based on the measured BER without FEC. Reed–Solomon RS(255, 239) coding was assumed, as well as a memoryless channel and orthogonal signaling. In this case, the symbol error $P_{S_{\rm FEC}}$ rate after FEC is related to the symbol error rate before without FEC (P_S) by

$$P_{S_{\rm FEC}} \approx \frac{1}{2^m - 1} \sum_{j=t+1}^{2^m-1} j \binom{2^m - 1}{j} P_s^j (1 - P_s)^{2^m-1-j}$$

TABLE I
THE MAXIMUM CAPACITY OF OUR PROPOSED NEXT GENERATION PON (N/A: NOT APPLICABLE, NF: NOISE FIGURE)

		JDS Driver H301-2310 (NF = 11 dB)				MITEQ Amplifier AM-1300 (NF = 1.6 dB)			
		without FEC		with FEC		without FEC		with FEC	
		Maximum Split: N	Margin [dB]	Maximum Split: N	Margin [dB]	Maximum Split: N	Margin [dB]	Maximum Split: N	Margin [dB]
Local Self-Seeding	10 km	4	0.6	16	2.4	**32**	**1**	**128**	**2.8**
	20 km	-	1.6	8	2.6	**8**	**2**	**128**	**0**
Remote Self-Seeding	10 km	-	5.1	16	1.4	**16**	**2.5**	**128**	**1.8**
	20 km	N/A	N/A	8	1.6	**N/A**	**N/A**	**64**	**2**

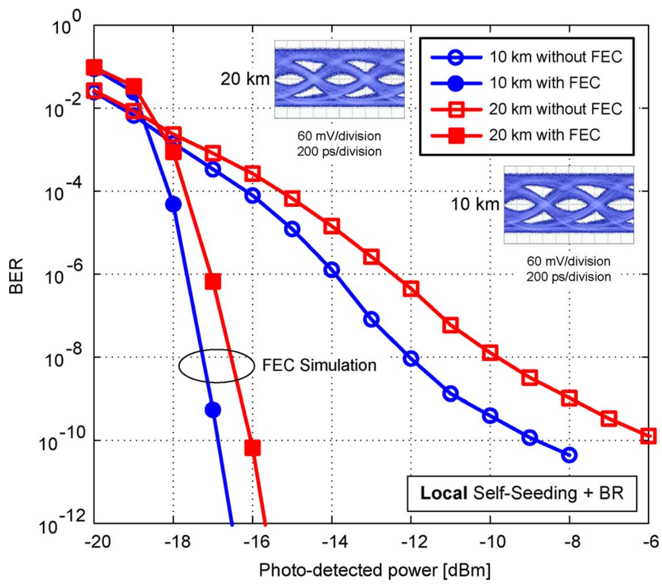

Fig. 8. BER performance at 1.25 Gb/s with local self-seeding and BR.

where $m = 8$ bits/symbol and $t = 8$ is the number of symbols errors that can be corrected per frame [24]. The symbol error rate P_S is related to the measured BER (P_B) by

$$P_s = 1 - (1 - P_s)^m$$

We anticipate a coding gain of 7.8 dB and 10 dB for the 10 km and 20 km cases, respectively.

V. Power Budget and Spectral Efficiency

Exploiting the legacy infrastructure requires that our SS-WDM channels have sufficient power to overcome the significant splitting losses incumbent in this architecture. Self-seeding improves the power margin, while noise cleaning and FEC improves performance (and spectral efficiency). With BER experiments and FEC simulations, we calculate the power budget for the proposed PON architecture in Fig. 3.

The BEDFA only compensates the losses of the $1 \times N$ coupler at the OLT, i.e., the BEDFA and the coupler act together as an integrated lossless coupler. The total losses L from the transmitter output to the receiver input for both uplink and downlink directions can be given by

$$L = 2L_{\text{BiDi}} + L_{\text{CWDM}} + \alpha_F D + 10 \log N$$

where L_{BiDi} and L_{CWDM} represent the insertion losses of the bidirectional modules and the CWDM filter, respectively. We adopt typically values $L_{\text{BiDi}} = L_{\text{CWDM}} = 0.5$ dB. The third term represents the propagation losses, where $\alpha_F = 0.2$ dB/km is the fiber attenuation around 1550 nm, and D is the length of the feeder plus the distribution drop fiber (DDF) in kilometers. The last term gives the splitting losses at the RN, where N is the number of splits, or the number of ONUs per OLT. In our analysis we consider a symmetric PON running at 1.25 Gb/s, a 2 km DDF, and a 10 or 20 km feeder without dispersion compensation.

From Fig. 8 we calculate the receiver sensitivity at 10^{-10} BER; 3 dB is added to the photo-detected power to account for the 1×2 coupler, so sensitivity is calculated at the input of the BR. Given the 4.5 dBm transmitter output power we compute the available power budget and therefore, the maximum PON capacity. The results are presented in the first two rows of Table I; please note that the remote self-seeding results will be discussed in the next section.

In our experiment we used a JDS H301-2310 as an RF amplifier after the PD. From the BER measurements we note that the receiver sensitivity is poor due to the 11 dB noise figure (NF) of that amplifier. Per [25], the NF of the RF amplifier at the receiver affects the sensitivity linearly. While we would have preferred running experiments with a low noise amplifier, none was available in the laboratory. To achieve a more realistic power budget, we repeat our calculations using specifications from the MITEQ AM-1300 low noise amplifier with only 1.6 dB NF. The receiver sensitivity is enhanced by 9.4 dB relative to our JDS driver, as is the available power budget. Table I shows in the first four columns results for the JDS driver, and in the final four columns results if the MITEQ amplifier was used instead.

Up to 32 users can be supported over a 10 km PON with self-seeded RSOA transmitters without FEC (a 1 dB link margin is remains). Over a 20 km feeder, 8 users can be supported with local self-seeding with 2 dB of link margin. Using FEC, up to 128 users can be supported. Another possibility would be to exploit the gain of the BEDFA at the central office so that up to 32 or even 64 users are supported without using a FEC. The total losses even for 1:64 splitting ratio and for a feeder length of 20 km, fall within Class B PONs where the total loss should range between 10 and 25 dB [2].

From a power budget perspective, a typical SS-WDM PON using AWGs at the RN experiences lower losses than our pro-

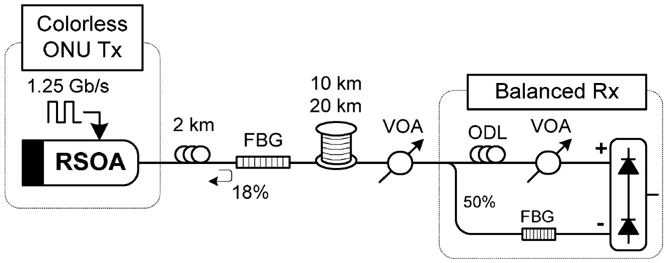

Fig. 9. Experimental setup for remote self-seeding.

posed SS-WDM PON architecture (the AWG typical insertion loss is only 5 dB). Further, the losses do not scale up with the number of users in the network. However using an AWG based RN imposes an upgrade of all users on the PON and no gradual roll-out. AWGs also make tight spacing of channels problematic if the advantages of noise cleaning are to be maintained. Our use of the BR allows dense channels, increasing spectral efficiency and bandwidth usage. When an AWG is used, the filtering effect occurs before the receiver, hence reduced noise cleaning gain with tight frequency spacing.

VI. Remote Self-Seeding and Possibility of a Colorless ONU Transmitter

Reduced inventory cost is often advocated to support colorless PON architectures. The proposed architecture requires two FBGs (one for self seeding and one for notch filtering) whose wavelength sets the wavelength deployed at the client, i.e., colored. To make the setup colorless requires the FBGs to be tunable. One solution would be to exploit a set-and-forget optical filter, i.e., a tunable FBG. To achieve low loss and wide spectral tunability, our approach uses reflective FBGs with strain tuning. Tuning of FBG filters over more than 100 nm has been demonstrated [26]. Another possibility exploits remote self-seeding by placing the self-seeding FBG at the RN so that the ONU transmitter is colorless. We investigate this solution, with the caveat that it will only address a colorless transmitter and not a colorless receiver. A tunable FBG is still be required at the receiver for colorless reception.

Remote self-seeding places the self-seeding FBGs at the RN so that the ONU transmitters become colorless. These FBGs are transparent to the downlink which is sent over another wavelength band. Placing the self-seeding gratings at the RN makes the design of the ONUs simpler, more compact, and lowers ONU cost. At the RN the FBGs would be exposed to greater temperature variations, but could be thermally isolated using a passive temperature-compensating package [23].

The experimental setup for the ONU remote self-seeding with a 2 km distribution drop fiber is shown in Fig. 9. The optimum grating again has 18% reflectivity; the transmitter output power is reduced to 4 dBm (vs. 4.5 dBm). The experiment is repeated for a 10 and 20 km feeder without dispersion compensation; a BR is used at the OLT. The BER performance is given in Fig. 10 for each feeder length. Compared to the local self-seeding, we note a power penalty of 1 dB for the 10 km case, and a BER floor around 10^{-9} starts to appear for the 20 km feeder. The degradation in performance is attributed to the additional dispersion added by the DDF. Eye diagrams at -12 dBm are also provided.

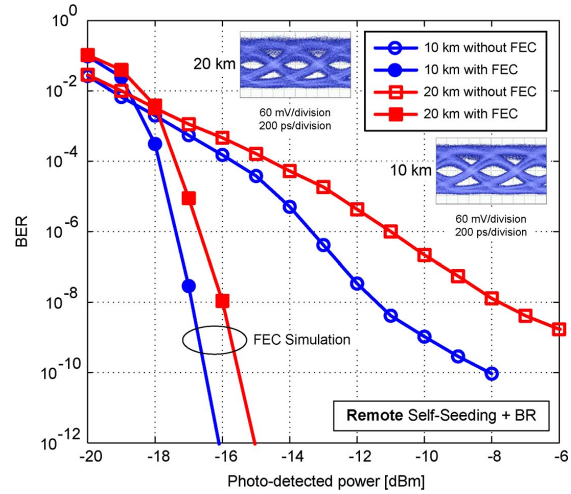

Fig. 10. BER performance at 1.25 Gb/s with remote self-seeding and BR.

The BER simulation using FEC is also presented; a coding gain of 8.3 dB is achieved for the 10 km case and the BER floor is eliminated for the 20 km link.

Finally, these results are used to generate a power budget, presented in the final two rows of Table I. For the transmitter output power of 4 dBm for remote self-seeding, we find the maximum PON capacity is unchanged when using FEC over a 10 km feeder; capacity is reduced from 128 to 64 for FEC over the 20 km link. Given the BER floor with remote self seeding, FEC is essential.

VII. Summary and Conclusion

In this paper we proposed, for the first time to our knowledge, a self-seeded RSOA-based transmitter with a balanced receiver for dense spectrum-sliced WDM over the legacy TDM PON infrastructure. Our solution provides a gradual upgrade and supports hybrid TDM and SS-WDM operation over the same PON infrastructure. Both local and remote self-seeding were demonstrated using a $p\%$ reflective FBG. The reflectivity was optimized to tradeoff self-seeding versus noise cleaning. The extinction ratio is also optimized to favor data erasure and reliable communication. For comparison we considered both a degenerate receiver with no filtering prior to photodetection and the conventional receiver with a CSF. We experimentally showed that despite a 3 dB penalty in implementing the BR, it outperforms the CR by preserving the noise cleaning without sacrificing spectral efficiency [15]. We measured BER better than 10^{-10} for local self-seeding over a 20 km feeder, whereas a BER floor around 10^{-9} appears for remote-self-seeding. For a 10 km feeder, error free is achieved for both cases.

Using our optimized transmitter with 4.5 dBm outpout power within a 25 GHz channel, and because of the use of the BR, even without FEC up to 32 users can be easily supported over the existing PON infrastructure; up to 64 users can be supported when using reasonable amplification at the OLT. We further simulated the coding gain when using a RS(255 239) FEC and showed that supporting 128 users is possible. Due to the flexibility in the design of FBGs compared to AWGs and due to the ability of the BR to maintain noise cleaning, our proposed PON achieves a higher spectral efficiency than that of traditional AWG-based SS-WDM PONs.

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