Cross-Seeding Schemes for WDM-Based Next-Generation Optical Access Networks

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***Abstract*—Rayleigh backscattering (RB) and Fresnel reflection (FR) effects can cause severe degradation on the performance of a WDM-PON system utilizing loop-back schemes that provide colorless upstream transmitters. We proposed cross-seeding schemes to overcome these problems and also to improve the utilization efficiency of the seeding lights. The operation principles of two types of cross-seeding schemes: mutual seeding and shared seeding are discussed in detail for different applications. A generalized formulation of the crosstalk from the RB and FR effects is derived for comparing the performance between a conventional WDM-PON and a cross-seeding WDM-PON. It is found that the cross seeding schemes can be most beneficial for the system with low loop-back gain or low reflection at the distribution fiber or drop fiber. This is especially advantageous for the shared seeding scheme in which the seeding light can be transmitted along a separate fiber with high power or by optical amplification such that the gain of the loop-back transmitter can be kept small. Application examples are used to demonstrate the merits and feasibility of the cross-seeding schemes.**

***Index Terms*—Reflective semiconductor optical amplifiers (RSOAs), wavelength-division-multiplexing passive optical network (WDM-PON).**

I. INTRODUCTION

IT IS expected that the future bandwidth requirement for end users of access networks will be dramatically increasing due to the increasing applications of various fixed or mobile broadband services. Next-generation access networks have to cope with the large bandwidth demands and versatile services with a reliable and cost-effective infrastructure [1], [2]. The other trend of an access network is to support a longer transmission distance and a greater number of end users. This is due to the needs for network consolidation and reduction of active sites that will move the switching facility and traffic aggregators from the access sites toward the point-of presence (PoP) of the service providers [3]. Thus, the optical access networks based on the wavelength-division-multiplexing (WDM) technique, especially the WDM passive optical networks (WDM-PONs), are attractive due to their potentials to fulfill all the above requirements [4], [5].

One of the keys for deploying WDM-PON access networks is the use of colorless transmitters at the optical networking units (ONUs) to reduce cost and avoid inventory issues. The most popular solutions to realize the colorless ONU transmitters are the so-called loop-back techniques, which require the transmission of seeding lights from the optical lightwave terminals (OLTs) to the ONUs for remodulation to carry the upstream signals. The signal lasers can be simultaneously used as the seeding light sources in order for reducing cost, but the modulation depth of the downstream signal needs to be compromised to minimize the resultant crosstalk to the upstream transmission [6], [7]. The compromise might be a concern for scaling the system to a longer reach or a larger number of users. Furthermore, these kinds of WDM-PON systems, no matter if they use seeding light or not, typically suffer from the transmission impairments due to the interferometric beat noise generated by Rayleigh backscattering (RB) and Fresnel reflection (FR). One of the solutions to overcome these problems is to use two fibers, one for downstream and the other for upstream transmission.

The cross-modulation schemes were proposed to reduce the performance degradation caused by the RB and FR effects and increase the utilization efficiency of fibers [8], [9]. In this work, we generalize the scheme to be a cross-seeding scheme for the WDM-PON networks that exploits the loop-back technique. This approach can avoid the use of special modulation formats or different carrier frequencies for the upstream and downstream transmission [10], [11]. The operation principles and the performance improvement on mitigating the RB and FR effects by using this approach will be described and analyzed. Experimental results will be presented to demonstrate the feasibility of this approach.

II. OPERATION PRINCIPLE

Conventional WDM-PON systems can use two fibers for respectively transmitting upstream and downstream channels so as to mitigate the degradation from the RB and FR effects, as shown in Fig. 1(a). In this architecture, the downstream signals are transmitted with multi-wavelength transmitters and demultiplexed to each ONU. The upstream signal for each ONU is transmitted by reusing the downstream light as the seeding light on which the upstream data are encoded by using an optical remodulator or an injection-locked Fabry-Perot (IL-FP) laser

Manuscript received June 14, 2011; revised September 12, 2011; accepted October 17, 2011. Date of publication November 02, 2011; date of current version December 09, 2011. This work was supported in part by the National Science Council, Taiwan under Contract NSC98-3114-P-011-001-Y and Contract NSC97-2218-E-011-007-MY3.

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Digital Object Identifier 10.1109/JLT.2011.2174194

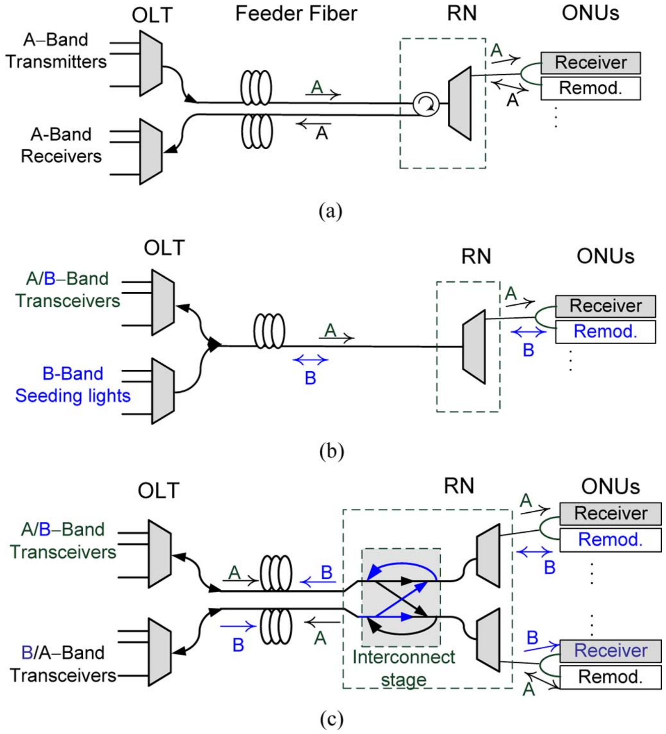


Fig. 1. Schematic diagram for (a) conventional two-fiber and (b) conventional one-fiber, and (c) the proposed cross-seeding WDM-PON systems.

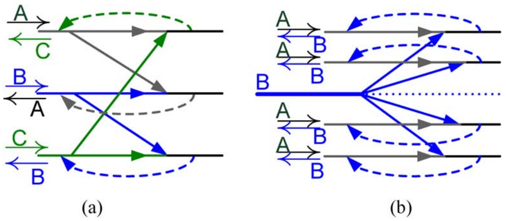


Fig. 2. Signal flow diagrams for the Interconnect stages of (a) mutual-seeding and (b) shared seeding WDM-PON systems with three or more signal fibers. The broken lines indicate the signal flow for the upstream channels.

TABLE I
COMPARISON AMONG WDM-PON ARCHITECTURES

	# of fibers	# of wave. bands	# of ONUs	Degraded by RB and FR	Crosstalk from signal in seeding light
Fig. 1(a)	2	1	N	Reduced	Yes
Fig. 1(b)	1	2	N	Severe	No
Fig. 1(c)	2	2	2N	Reduced	Yes
Shared seeding Fig. 2(b)	m+1	2	mN	Reduced	No

*N is the number of wavelengths used in each wavelength band; m is the number of signal fibers.

[12]–[14]. The re-modulator can be a reflective semiconductor optical amplifier (RSOA), an external modulator, a reflective electroabsorption modulator (REAM), or an integrated modulator with a semiconductor optical amplifier (SOA) [15]–[17].

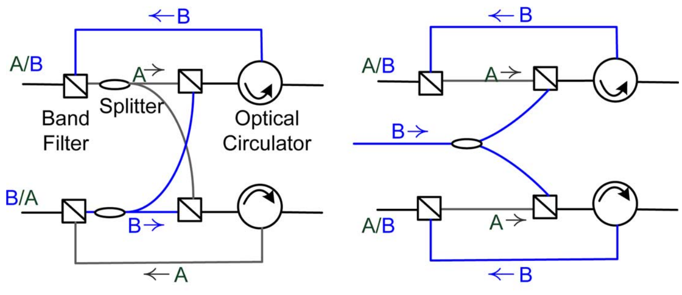
An alternative structure, as shown in Fig. 1(b), is to send additional seeding lights from the OLT to the ONUs for carrying the upstream signals. The most popular scheme of this type is to use amplified spontaneous emission (ASE) light sources as the seeding lights and IL-FP lasers (or RSOAs) as the colorless upstream transmitters. With the additional continuous-wave (CW) seeding lights in a different wavelength band from the downstream wavelengths, there will be no crosstalk problems onto the upstream signals from the downstream signals. However, due to the co-transmission in the same fiber for the seeding lights and upstream signals, the upstream signals are still influenced by the RB and FR effects.

The concept of the WDM-PON architecture using the cross-seeding scheme is illustrated in Fig. 1(c). The architecture can be regarded as two WDM-PON systems interconnected at the RN such that the downstream lights of one system can be used as the seeding lights for the other system to transmit upstream signals. With this kind of configuration, the upstream wavelengths (Band B for the upper fiber path) are different from the downstream ones (Band A). The RB and FR effects can be minimized since the reflected signals from the downstream channels can be easily filtered out by the upstream receivers. The cross-seeding scheme also avoids the use of additional seeding light sources.

The cross-seeding scheme can be applied to a system with more than two feeder fibers. In general, this scheme can be classified as two types: mutual-seeding and shared seeding, as illustrated in Fig. 2. For the mutual seeding approach, every set of two fibers is interconnected at the RN with different assignments of wavelength bands. For example, three wavelength bands are needed for the case shown in Fig. 2(a). The returned (upstream) signals are always at a different wavelength band from the downstream channels along the same feeder fiber. In practical applications, there is no need to use more than three wavelength bands when more fiber are involved since the same wavelength bands can be reused as long as the two wavelength bands for the upstream and downstream transmissions in a feeder fiber are different.

For the shared seeding configuration, one feeder fiber, called the seeding fiber here, is designated for transmitting the seeding lights, which are distributed to the other signal fibers at the RN to serve as their cross-seeding lights for upstream transmissions, as shown in Fig. 2(b). All signal fibers can use the same set of two wavelength bands for upstream and downstream transmission to reduce the RB effects. This configuration is advantageous when many fibers are used in the same access networks because only one set of seeding lights are used to serve a great number of end users. Since the cost of seeding lights is shared by many users, CW seeding lights can be used to avoid the downstream crosstalk to the upstream signals, as happened in the mutual seeding case. It can also provide the flexibility to implement other functions to the access networks along the seeding fiber, such as remote optical amplification, signal monitoring, and the protection of paths. On the other hand, the seeding fiber can still be used to transmit signals to the other set of users, as indicated by the dotted line in Fig. 2(b), or other services if needed.

Table I compares the three architectures shown in Fig. 1. Two types of crosstalk impairments are considered here for the upstream transmission: one is the crosstalk from the signals



(a) (b)

Fig. 3. Implementation of the interconnect stage for two signal fibers: (a) mutual seeding and (b) shared seeding.

embedded in the seeding light, which occurs when the downstream lights are reused as the seeding light; and the other is the crosstalk caused by the RB and FR effects for signal transmission in the feeder and drop fibers. It is clear that a cross-seeding WDM-PON can have the advantage of reducing the RB and FR effects. Though two feeder fibers are used, the system can provide services to twice the number of users if they can be connected by the same feeder path. The crosstalk from the signals embedded in the seeding light can be avoided by using the shared seeding scheme.

The interconnect stage can be simply implemented with passive optical components, as shown in Fig. 3 for the mutual seeding and shared seeding cases when two signal fibers are used. The implementation can be extended with ease for the systems with more fibers. The components used in Fig. 3 do not consume electrical power, so the cross-seeding access networks retain the merits of passive optical networks. Moreover, the interconnect stage uses only wavelength insensitive or wavelength band filters, without the necessity to process individual channels. This keeps the remote node at a simple configuration.

For clarity, the upper fiber path is used as the example for illustrating the operation principle. For the mutual-seeding case, the downstream signals of Band A pass through the first band filter and are split into two portions. Half of the power of each downstream signal goes straight through the interconnect stage for signal reception at the ONU, and the other half is directed to the lower fiber path to serve as the seeding light. The seeding lights of Band B that come from the lower fiber path are combined by the second band filter and directed to the upper-path ONUs, where each seeding light is reused to carry the upstream signals by injection locking or remodulation. The multiplexed upstream signals from the output of the colorless transmitters (of Band B) are redirected by the optical circulator to the bypass path, combined by the first band filter, and then transmitted back to the upstream receivers along the upper fiber path through which the A-band downstream signals pass. Therefore, the downstream and upstream signals in the same feeder fiber are at different wavelength bands such that the RB and FR effects can be reduced. The signal direction is reversed for the lower fiber path.

For the shared-seeding case, as shown in Fig. 3(b), the path for the seeding lights is similar to that in the mutual-seeding case but without the splitting of downstream signals (of Band A). This avoids the 3-dB splitting loss to the downstream signals and can be beneficial for long-reach (LR) access. Since the seeding lights are distributed to multiple signal fibers, a large transmitted power and/or optical amplification needs to be used to compensate the splitting loss of seeding lights when the number of signal fibers increases.

The scheme can be used for WDM-POM systems that utilize IL-FP lasers or any kind of remodulators as the colorless transmitters at ONUs. Since the next-generation optical access may support a greater number of users to a longer reach, it is expected to have multiple fibers running from one central office to a remote node. Therefore, the proposed approach can be very useful to solve the RB and FR impairments by simply interconnecting the fiber paths at the RN.

The interconnect stage can be implemented in different ways and can include other functionalities if necessary. For example, it can include the optical signal processing modules when special modulation formats are used for carrying the signals [18], [19]. In fact, the cross-seeding scheme is mainly for reducing the signal degradation caused by the reflections. It can be combined with other schemes to mitigate the crosstalk on the upstream signals caused by the modulated downstream signals. The spectral filtering technique was demonstrated with the cross-seeding scheme to allow the use of low-extinction-ratio downstream signals in order to reduce the crosstalk [7], [8]. Downstream transmission with phase modulation formats can also be used with the cross-seeding to avoid the crosstalk [20].

The two wavelength bands along the two fibers for the mutual-seeding case can be used to transmit different signal formats for different applications. This is useful for multi-service integration, like integration of data and video as well as the integration of fixed and mobile networks, and so on. Optical amplification can also be included to boost the signal strength for long-reach applications [21]–[23].

One of the promising applications for the shared seeding scheme is its combination with coherent detection scheme for long-reach WDM-PON systems. The coherent detection can significantly improve the receiver sensitivity and extend the transmission distance, which is critical for a LR access network. A simple way of realizing LR WDM-PON systems is to use the seeding lights as the local oscillators for the coherent detection of the upstream data [24]. Such type of coherent detection can benefit from the shared seeding scheme because the seeding lights can be shared by multiple fibers to further reduce the cost. Moreover, simple coherent receivers without the needs of complicated signal processing can be used when CW seeding lights are used [25].

The cross-seeding scheme can also be used for providing dynamic bandwidth assignment and/or optical path protection for the WDM-PON systems. Since the downstream signals can reach both groups of receivers for mutual seeding case, the lights that serve originally as the seeding lights for re-modulating can also be received by adding another set of receivers at the ONUs. These receivers can provide additional bandwidth to the end users [26]. With this capability, the path protection mechanism can also be easily realized by setting up the backup routing plan at the OLT. The additional receiver can temporarily replace the original downstream receiver when it fails. For the shared seeding case, one seeding wavelength (of Band B) can protect multiple paths, one for each fiber.

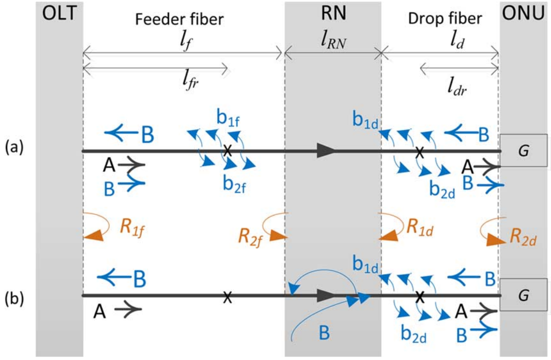


Fig. 4. Schematic of Rayleigh scattering and Fresnel back reflection in (a) conventional and (b) upper arm of the cross-seeding WDM-PON system.

III. REDUCTION IN RAYLEIGH BACKSCATTERING

The influence of RB and FR on the system performance of a WDM-PON structure has been investigated in detail [27]–[30]. There are two types of RB and FR effects that can degrade the upstream transmission: one arises from the reflection of the downstream seeding light (Type I); and the other from the reflection of the upstream signal (Type II). For simplicity of discussion, and because the combined distribution and drop fibers have similar effects on RB and FR degradation, we will use the term drop fiber for the final fiber segment running from the RN to the ONU. The reflection of the upstream signals can be a dominant beating noise when a high-gain remodulator, like a RSOA, is used as the colorless transmitter [27].

Fig. 4 shows the simplified system models for the conventional and cross-seeding WDM-PON systems. This figure shows only the major beating noise sources for the upstream transmission. The noise denoted as b_{1f} in the diagram represents the reflection of the seeding light B by the RB and FR effects in the feeder fiber, while b_{1d} is the noise arising from the same mechanism in the drop fiber. The noises denoted as b_{2f} and b_{2d}, stand for the reflections of the upstream signals by the RB and FR effects in the feeder fiber and drop fiber, respectively. These two reflections will be amplified by the gain of the loopback transmitter and directed to the upstream receiver at the OLT. When a cross-seeding scheme is utilized, the noises b_{1f} and b_{2f} occurring in the feeder fiber are blocked by the cross-seeding configuration of the RN.

In the following analysis, the beating noises from cascaded multiple scatterings and/or reflections are neglected by assuming that each single RB and FR effect is relatively small. Only the beating noise to the upstream transmission is considered here. The total beating noise power for the received upstream signal in a conventional WDM-PON system can be written as

$$P_c = P_{c1} + P_{c2} \tag{1}$$

where P_{c1} and P_{c2} represent the crosstalk power from Type-I and Type-II beating noise, respectively. These two terms can be expressed as

$$P_{c1} = P_{\text{seed}}\left(R_{1f} + R_{1d} l_{\text{RN}}^2 l_f^2\right) \tag{2}$$

$$P_{c2} = P_{\text{ONU}}\left(R_{2f} l_{\text{RN}}^2 l_d^2 + R_{2d}\right) G l_t \tag{3}$$

where P_{seed} and P_{ONU} are the transmitted seeding power at OLT and transmitted upstream power from the ONU transmitter, respectively. G is the gain of the loop-back ONU transmitter. R_{1f} is the effective reflection of the downstream seeding light seen at the output of the OLT. It may include the contribution from both the RB and FR effects occurring in the feeder fiber. Likewise, R_{1d} is the effective reflection of the downstream seeding light occurring in the drop fiber seen at the output of the RN. R_{2f} is the effective reflection of the upstream signal in the feeder fiber seen at the output of the RN. R_{2d} is the effective reflection of the upstream signal seen at the output of the ONU.

These effective reflection coefficients are illustrated in Fig. 4 and can be written as

$$R_{1f} = B\left(1 - l_f^2\right) + r_f l_{fr}^2 \tag{4a}$$

$$R_{1d} = B\left(1 - l_d^2\right) + r_d l_d^2 l_{dr}^{-2} \tag{4b}$$

$$R_{2d} = B\left(1 - l_d^2\right) + r_d l_{dr}^2 \tag{4c}$$

$$R_{2f} = B\left(1 - l_f^2\right) + r_f l_f^2 l_{fr}^{-2} \tag{4d}$$

where B is the Rayleigh scattering coefficient. The first term in each of these four equations considers the RB effect in the feeder or drop fiber, while the second term considers the FR effects occurring in the feeder or drop fiber. In (2) to (4), l_f, l_d, l_{RN} stand for the loss of the feeder fiber, drop fiber, and remote node, respectively. l_{fr} is the fiber propagation loss from the OLT to the discontinuity that causes the FR. Likewise, l_{dr} is the fiber propagation loss from the ONU to the discontinuity that causes the FR. The FR effects occurring in the RN can also be included by regarding them as occurring at the end of the feeder fiber or drop fiber. The total single-pass loss of the system is $l_t = l_f l_{\text{RN}} l_d$.

For a conventional WDM-PON without any amplification at the RN, the crosstalk is typically dominated by the terms associated with R_{1f} and R_{2d}. That is, (1) can be simplified to

$$P_c = P_{\text{seed}} R_{1f} + P_{\text{ONU}} R_{2d} G l_t \tag{5}$$

where $P_{\text{ONU}} = P_{\text{seed}} G l_t$. For cross-seeding WDM-PONs, there is no contribution from the R_{1f}-term since the seeding light does not propagate along the same fiber. The term associated with R_{2f} is blocked by the band filter and optical circulator in the RN. Therefore, only the FR and RB occurring in the drop fiber can influence the upstream transmission in a cross-seeding WDM-PON. That is, the cross-seeding scheme eliminates Type-I beating noise. The crosstalk for a cross-seeding WDM-PON can be written as

$$P_c = P_{\text{ONU}} R_{2d} G l_t + P_{\text{seed}} R_{1d} l_{\text{RN}}^2 l_f^2. \tag{6}$$

The crosstalk-to-signal ratio (C/S) for the upstream signal can thus be given by

$$\frac{C}{S} = \frac{R_{1d}}{G l_d^2} + R_{2d} G, \quad (\text{cross-seeding}). \tag{7}$$

The C/S value can be approximated by $R_{2d}G$ for a large ONU gain. It can be shown that the minimal value of C/S occurs at the optimal gain of

$$G_{\text{opt}} = \frac{1}{l_d}\sqrt{\frac{R_{1d}}{R_{2d}}}. \tag{8}$$

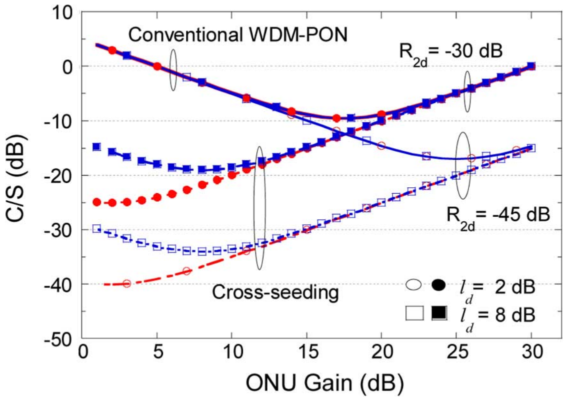


Fig. 5. Crosstalk to signal ratio of upstream signals versus ONU gain for the conventional and cross-seeding WDM-PON architecture. In the calculation, $l_t = 20$ dB, $R_{1f} = -35$ dB, $R_{1d} = R_{2d.} = -45$ dB or -30 dB, $l_d = 2$ or 8 dB.

Thus the minimal C/S is given by

$$\left(\frac{C}{S}\right)_{\text{min,cross-seeding}} = \frac{2}{l_d}\sqrt{R_{1d}R_{2d}} \tag{9}$$

for a cross-seeding WDM-PONs. In contrast, the C/S ratio for a conventional WDM-PON can be derived from (5) as

$$\frac{C}{S} = \frac{R_{1f}}{Gl_t^2} + R_{2d}G \quad (\text{conventional}). \tag{10}$$

$$G_{\text{opt}} = \frac{1}{l_t}\sqrt{\frac{R_{1f}}{R_{2d}}} \tag{11}$$

and the minimal value is given by

$$\left(\frac{C}{S}\right)_{\text{min,conventional}} = \frac{2}{l_t}\sqrt{R_{1f}R_{2d}}. \tag{12}$$

The improvement ratio on the C/S ratio by the cross-seeding WDM-PONs over the conventional WDM-PONs can be expressed as

$$\chi \equiv \frac{(C/S)_{\text{min,conventional}}}{(C/S)_{\text{min,cross-seeding}}} = \frac{l_d}{l_t}\sqrt{\frac{R_{1f}}{R_{1d}}}. \tag{13}$$

Considering the case in which all the Fresnel reflections are carefully dealt with, the reflection terms in (4) are dominated by the Rayleigh scattering. The improvement factor can be simplified as l_d/l_t by further assuming that both feeder fibers and drop fibers are longer than 20 km.

Fig. 5 shows the calculated C/S ratio by using (7) and (10). The minimal C/S for the WDM-PONs using the cross-seeding scheme occurs at a lower ONU gain and is at least 10 dB lower than that for conventional WDM-PONs for the calculated conditions. A loop-back transmitter (e.g., a RSOA) with low gain can be used in an ONU if the seeding light reaching the ONU is strong enough to support satisfactory received power for the upstream transmission. This is especially beneficial for the shared seeding cases. Since the seeding lights of the shared-seeding case are transmitted through a separate fiber, it is relatively flexible to manipulate the power of seeding lights by using high-power lasers or by exploiting distributed Raman amplification for the seeding light. With strong seeding light injection into the loop-back transmitter, a smaller gain or no gain can be used for the transmitter; so the upstream transmission can be shielded from the degradation of FR or RB effects.

Another condition for comparing the C/S ratio between a conventional WDM-PON and a cross-seeding WDM-PON is to set the ONU gain at the value to compensate the total single-pass loss, i.e., $G = 1/l_t$. At this condition, the improvement ratio becomes

$$\chi' \equiv \frac{(C/S)_{G=1/l_t,\text{conventional}}}{(C/S)_{G=1/l_t,\text{cross-seeding}}} \approx 1 + \frac{R_{1f}}{R_{2d}}. \tag{14}$$

For WDM-PONs with relatively short drop fibers, R_{1f} will be larger than R_{2d} if all the FB effects from component interfaces or fiber discontinuities are well engineered such that the dominant reflection is from the RB effect. Under this condition, the cross-seeding scheme can still reduce the C/S value even at a high ONU gain. The improvement can be about 10 dB when $R_{1f} = -35$ dB and $R_{2d} = -45$ dB, as shown in Fig. 5.

The power penalty caused by the resultant C/S ratio in a WDM-PON system depends on the linewidth of the light source, receiver bandwidth, and relative polarization between upstream signals and the unwanted reflected components [27], [29]. It has been well known that the power penalty can be reduced by using a broadband light source, like an ASE source, as the seeding light. However, the RB and FR effects can still limit the system performance of ASE-seeded WDM-PON systems for the cases of long transmission distance and/or large ONU gain [31].

IV. APPLICATIONS

In this section, two examples of applying the cross-seeding schemes to WDM-PON networks will be addressed.

A. *Mutual-Seeding for RSOA-Based WDM-PONs*

The use of the cross-remodulation scheme to reduce Rayleigh scattering effects on WDM-PON systems was demonstrated by using C- and L-band light sources [8]. Externally modulated L-band light sources were used for the upstream transmission. Since the seeding lights are also used to carry downstream signals, the performance of the upstream signals is still limited by the crosstalk noise from signals embedded in the downstream seeding light, in addition to the degradation from the RB and FR effects. In order to minimize the crosstalk noise, we demonstrate here the use of directly modulated lasers (DMLs) as the downstream transmitters for both wavelength bands such that the spectral filtering scheme can be used to reduce the crosstalk. The system architecture is similar to the one shown in Fig. 1(c). The C-band of DWDM wavelengths are divided into two subbands, CB (blue) and CR (red) bands. The operation principle of the mutual seeding is the same as the description in Section II with subbands CR and CB being the bands A and B, respectively. A RSOA is used at each ONU to serve as the upstream transmitter.

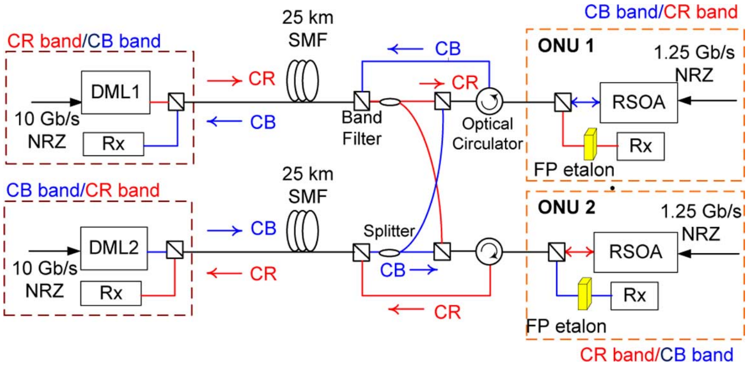


Fig. 6. Experimental setup for mutual-seeding WDM-PONs.

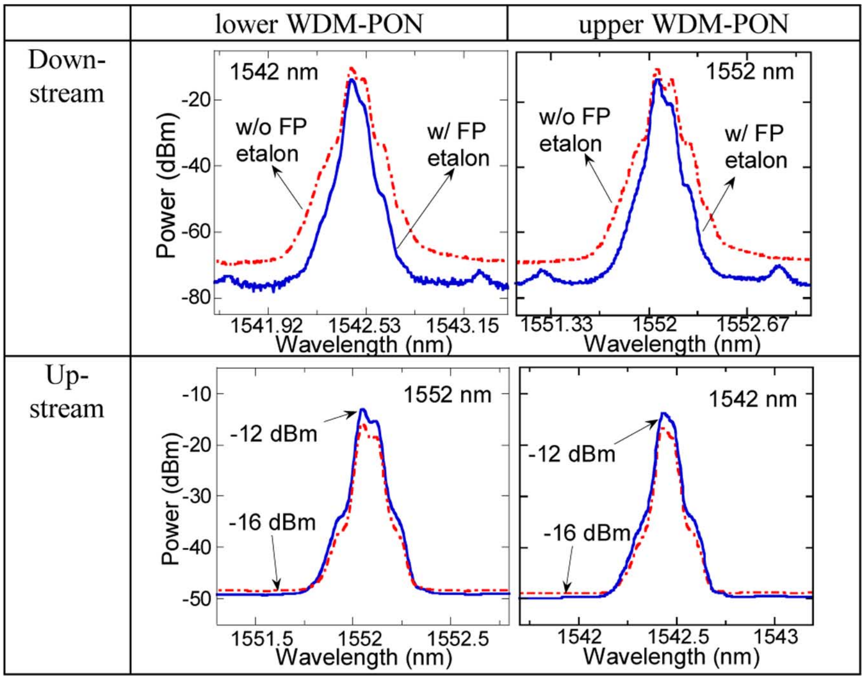


Fig. 7. Optical spectra of upstream and downstream signals for the upper and lower WDM-PONs.

Fig. 6 shows the simplified experimental setup for demonstrating the performance of mutual seeding. The mutual seeding interconnect stage at the RN includes only passive optical components. The circulators are used for separating the injected light and the remodulated signal to different fiber paths. They also avoid a 3-dB loss for the upstream traffic by not passing it through the 3-dB coupler. The CB/CR-band filter is used to combine or separate the signals for the wavelength bands. In each ONU, a CR/CB-band filter is used to separate and direct the signals of the two wavelength bands onto the receiver and RSOA, respectively. By comparing this layout with a typical WDM-PON with DMLs and RSOAs [29], the extra devices in the new structure are the CR/CB-band filters, which can be low loss and low cost. The data rates for the downstream and upstream signals in the experiments are 10 and 1.25 Gb/s, respectively.

Two DMLs of 1542.44-nm (CB-band) and 1552.04-nm (CR-band) wavelengths are used to demonstrate the mutual seeding concept. When the downstream signals are reused as the seeding light, the extinction ratio (ER) of the downstream signals must be compromised. The ER needs to be low to suppress the in-

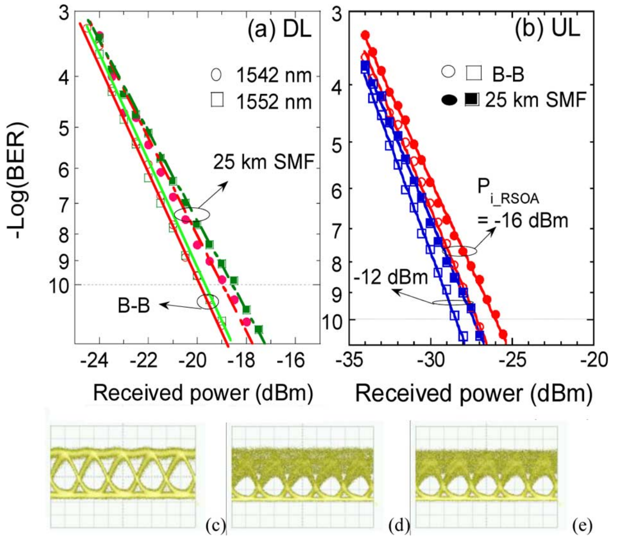


Fig. 8. Measured BER curves for (a) downstream and (b) upstream signals, and eye-diagrams after 25-km SMF transmission for (c) CR downstream signal, (d), (e) upstream signal when the injected power to the RSOA is −16 and −12 dBm, respectively, in a mutual seeding WDM-PON.

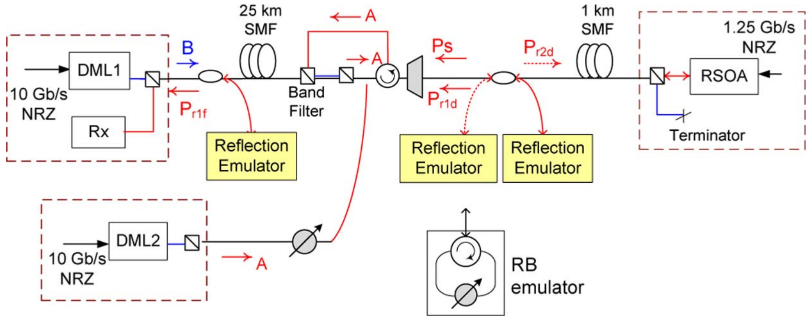


Fig. 9. Experimental setup for measuring the effects of RB and FR on the performance of a mutual-seeding WDM-PON.

duced crosstalk on the upstream data but should be high to avoid a low-ER power penalty for the downstream signals. The compromise can be removed by adding a simple Fabry-Perot (FP) etalon before the downstream receiver to enhance the received ER [7], [8]. The etalon can reshape the signal spectrum and then the waveform due to the separation of the on- and off-level spectra from the modulation induced adiabatic chirp. Thus, each receiver at an ONU is equipped with a FP etalon. The same etalon can be used to reshape different WDM channels as long as its FSR matches the channel spacing. Thus, all ONUs are still colorless. To obtain a stable ER enhancement may require wavelength tracking between the signal wavelength and the spectral peak of the etalon. In the experiments, the ER of the downstream signal is 3 dB.

The transmitted powers for the CB-band and CR-band DMLs are 5.4 and 6.2 dBm, respectively. The data patterns for modulating the DML and RSOA are $2^{31} - 1$ and $2^{15} - 1$ pseudo-random binary sequences (PRBS), respectively. The output saturation power and the optical small-signal gain of the RSOA are +3.0 dBm and 20 dB, respectively. The peak wavelength and 3-dB bandwidth of the RSOA gain spectrum at 60-mA bias are 1557 and 60 nm, respectively. The injected power of the downstream signal into the RSOA is fixed at −12.0 dBm (or −16.0 dBm) by using an optical attenuator. The insertion loss of the CB/CR-band filter is about 0.4-dB. The etalon has a FSR of 100 GHz and a 3-dB bandwidth of 0.136 nm. The insertion loss of the FP etalon is 3 dB due to the input/output coupling losses, which can be reduced by using better alignment and packaging schemes.

The output spectra of the RSOA for the upstream and downstream signals are shown in Fig. 7. The spectral filtering by the FP etalon can improve the ER from 3 to 8 dB for the downstream signals. It also suppresses the out-of-band noise by about 5 dB. The ER of the remodulated upstream signals is about 10 dB for both WDM-PONs. From the optical spectra, the optical signal-to-noise ratio (OSNR) for the upstream signal is, respectively, 32 and 36 dB with an input seeding light power of −16 and −12 dBm into the RSOA.

Fig. 8(a) and (b) shows the measured bit error rate (BER) for the downstream and upstream channels, respectively. The signals are detected with PIN receivers. The downstream channels have about 1.2 and 0.8 dB of power penalty at a $\mathrm{BER} = 10^{-10}$ after 25-km transmission along the upper (CR-band) and lower (CB-band) fiber paths, respectively. The eyediagram for the downstream CR-band signal is shown in Fig. 8(c). The power penalty for downstream transmission is mostly due to dispersion from the frequency chirp. For the upstream signals, Fig. 8(b) shows the measured BER under −16 or −12 dBm of input seeding power to the RSOA. For both seeding power levels, the upstream signals have about a 1.1-dB power penalty at a $\mathrm{BER} = 10^{-10}$ after 25-km transmission, compared to the back-to-back case. The power penalty is mainly due to the residual crosstalk from the downstream signals embedded in the seeding light, as indicated in Fig. 8(d)–(e). It can be seen from this result that the performance degradation by the crosstalk from the downstream signals is limited to a reasonably small value by the use of the spectral filtering scheme.

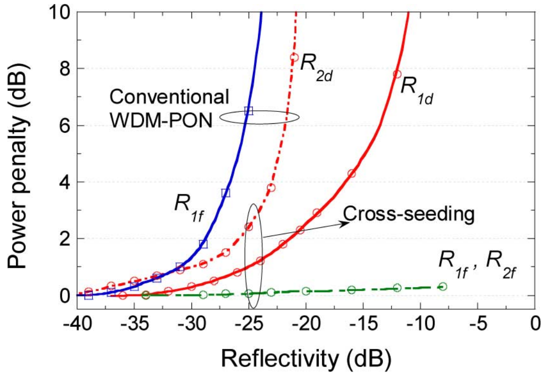
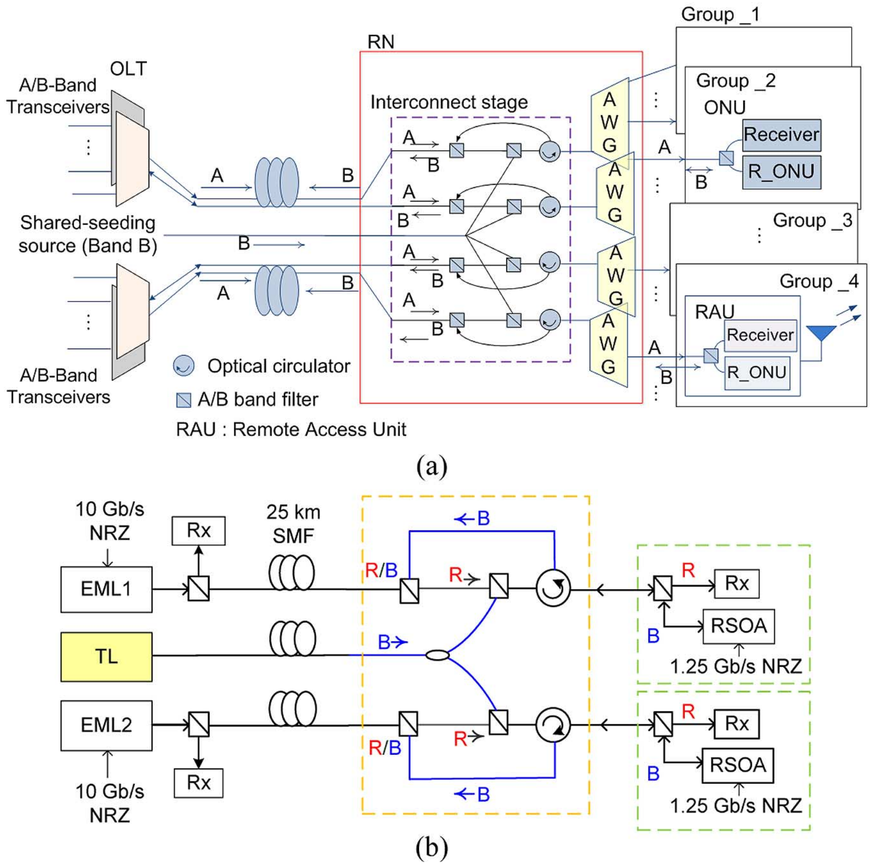


Fig. 10. Comparisons of power penalty caused by each reflection element between conventional and cross-seeding WDM-PONs.

The upstream transmission with a larger input power to the RSOA has better receiver sensitivity due to its larger OSNR, as indicated in Fig. 7, and stronger saturation of the SOA that leads to a stronger suppression of the embedded downstream signal. Since the upstream signals are riding on the downstream signals of 3-dB ER for both branches of WDM-PONs, similar performance is expected for the upstream signals of both subbands. From Fig. 8, good performance for both transmission directions can be obtained by using the mutual-seeding scheme.

The experimental setup with reflection emulators shown in Fig. 9 is used for investigating the reflection effects on the system performance of the mutual-seeding WDM-PONs. The reflection coefficient is adjusted by using a ring structure formed by an optical circulator and attenuator. The input power to the RSOA is −16 dBm, leading to 11-dB RSOA gain. The power penalty caused by each reflection is measured separately and shown in Fig. 10. As expected, the reflections occurring



(a)

(b)

Fig. 11. Schematic diagram (a) and simplified experimental setup (b) for the proposed shared-seeding WDM-PON systems.

in the feeder fiber have negligible effects on the cross-seeding WDM-PONs. The most severe degradation comes from the reflection of the upstream signal (R_{2d}), which can be less than 1 dB as long as the reflection is smaller than -30 dB. The tolerance to the reflection R_{1d} is about -25 dB under 1-dB power penalty criterion. When a larger reflection occurs, a cross-seeding WDM-PON can provide a better performance than a conventional system.

B. Shared Seeding WDM-PON Systems

As stated previously, the shared seeding schemes can be exploited when multiple fibers are used to connect a central office to a remote node in order to support hundreds of ONUs and/or different services, as illustrated in Fig. 11(a). All signal fibers can use the same set of wavelength channels of, say Wavelength Band A, for downstream transmission. One fiber is used as a seeding fiber for transmitting the seeding lights of Wavelength Band B. CW seeding lights can be used to avoid the crosstalk to the upstream signals from the downstream signals embedded in the seeding light. The operation principle of the shared seeding is described in Section II.

The experiments for demonstrating the performance of shared-seeding WDM-PONs are carried out with a simplified setup, as shown in Fig. 11(b). A seeding fiber is used to support seeding lights to two WDM-PON systems. A tunable laser source with 1540-nm wavelength is used as the shared-seeding light source. The output power of the seeding light is $+5$ dBm. Two EMLs of 1550 and 1551.8 nm wavelengths are respectively used as the downstream transmitters for the two WDM-PONs. They are modulated with 10 Gb/s $2^{31}-1$ NRZ PRBS patterns. The extinction ratios are 9.85 and 9.62 dB, respectively. The average transmitted powers are -2 and -2.68 dBm, respectively. CR/CB subband filters are used to combine or separate the seeding light and the signal lights. For upstream transmission, RSOAs are again used as the upstream transmitters. The seeded power into the RSOA is adjusted by using an optical attenuator to be -12 or -16 dBm. The corresponding output gains for the two input power levels are 7.3 and 8.1 dB, respectively. The RSOAs are modulated with 1.25 Gb/s PRBS data.

Fig. 12(a) shows the measured BER curves for the 10 Gb/s downstream signals of which the eysdiagram is sown in Fig. 12(c). After 25-km SMF transmission, the power penalty is less than 1.2 dB, mostly due to the fiber dispersion. For upstream transmission, the results shown in Fig. 12(b) indicate less than 0.6 dB of power penalty after 25-km SMF transmission by comparing to the back-to-back cases. However, the upstream transmission with lower seeding light power (-16 dBm) has a slightly worse bit error rate. By checking the corresponding eye-diagrams [see Fig. (d) and (e)] and optical spectrum, the upstream signal with lower seeding power had a smaller optical signal to noise ratio, due to a stronger amplified spontaneous emission (ASE) noise. This proves that the dominant impairment for the experimental conditions is the ASE

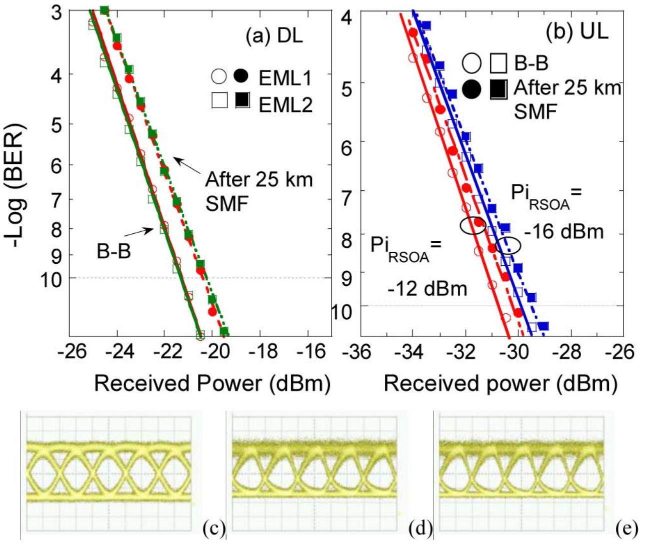


Fig. 12. Measured BER results of (a) the downstream 10 Gb/s and (b) the upstream 1.25 Gb/s signal. The eye-diagrams after 25-km SMF transmission for (c) downstream signal, (d), (e) upstream signal when the injected power to the RSOA is −16 and −12 dBm, respectively.

noise rather than the Rayleigh scattering. In a practical system design, a low input power to the RSOA is desired in order to increase the optical loss budget between OLT and ONU as long as good enough OSNR is assured. The power penalty of upstream transmission for the shared-seeding case is smaller than that for the mutual seeding case (see Fig. 8) because the former case is free from the crosstalk caused by the embedded downstream signals in the seeding light.

V. CONCLUSION

The well-known transmission impairments from the RB and FR effects on WDM-PON systems using the loop-back technique for realizing colorless ONU transmitters can be reduced by the proposed cross-seeding architectures. The mutual seeding scheme can provide twice the system capacity with reduced crosstalk from the reflection effects. It has a simple structure by interconnecting two parallel WDM-PONs operating at different wavelength bands. Since very few extra components are added to the system, the two wavelength bands can be used to serve more users or to provide different services. The shared-seeding scheme can reduce the reflection effects and also can avoid the crosstalk caused by the embedded downstream signals in the seeding light, occurring in a conventional WDM-PON and the mutual seeding WDM-PON. Though an additional fiber for transmitting the seeding lights is needed, the seeding fiber can be shared by multiple parallel WDM-PONs. It can also be used for carrying extra service signals.

The reduction in the crosstalk-to-signal ratio by the proposed cross-seeding schemes is verified by theoretical analyses. The minimal C/S ratio for the cross-seeding schemes can be much better than that for the conventional architecture, especially when the return loss associated with the drop fibers can be carefully managed. The improvement by the cross-seeding scheme can benefit the most by using a small ONU gain. This is especially suitable for the shared seeding cases since relatively strong seeding light can be delivered to the ONU. Experimental demonstration of the mutual seeding and shared seeding WDM-PONs are carried out by using RSOAs as the ONU upstream transmitters. These results verify that the cross-seeding scheme can indeed reduce the RB and FR effects.

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