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DOWN-LINK CATV/FTTH AND UP-LINK FTTH TRANSPORT SYSTEMS BASED ON REFLECTIVE SEMICONDUCTOR OPTICAL AMPLIFIER

C.-L. Ying

Department of Electronic Engineering
Jinwen University of Science and Technology
Taipei County 231, Taiwan, R.O.C.

C.-H. Chang

Institute of Electro-Optical Engineering
National Taipei University of Technology
Taipei 106, Taiwan, R.O.C.

Y.-L. Houng

Department of Electronic Engineering
Jinwen University of Science and Technology
Taipei County 231, Taiwan, R.O.C.

H.-H. Lu

Institute of Electro-Optical Engineering
National Taipei University of Technology
Taipei 106, Taiwan, R.O.C.

W.-S. Tsai

Department of Electrical Engineering
Mingchi University of Technology
Taipei County 243, Taiwan, R.O.C.

H.-S. Su

Institute of Electro-Optical Engineering
National Taipei University of Technology
Taipei 106, Taiwan, R.O.C.

Corresponding author: H.-H. Lu (hhlu@ntut.edu.tw).

Abstract—A down-link CATV/fiber-to-the-home (FTTH) and up-link FTTH transport system employing a reflective semiconductor optical amplifier (RSOA) as wavelength reuse and remodulation schemes is proposed and experimentally demonstrated. By using −1 side mode injection-locked/optoelectronic feedback techniques, brilliant performances of carrier-to-noise ratio (CNR), composite second-order (CSO), composite triple beat (CTB), and bit error rate (BER) were obtained for downlink transmission; low BER value was also achieved for up-link transmission over a 50-km single-mode fiber (SMF) transmission. Such a CATV/FTTH transport system is suitable for broadband access fiber networks.

1. INTRODUCTION

It is generally agreed that CATV and fiber-to-the-home (FTTH) applications provide the ultimate in bandwidth and flexibility as considering broad bandwidth and high-speed data rate access, especially with bandwidth of 550–750 MHz and data rate of 1.25–2.5 Gbps [1, 2]. The transmission of CATV signals is the first large scale commercial application of analog lightwave transport systems, and the transmission of FTTH signals is the first large scale commercial application of digital lightwave transport systems. CATV integration with FTTH transport systems has provided a way to deliver analog CATV and digital baseband (BB) signals simultaneously. The transmission performances of CATV/FTTH transport systems are evaluated by parameters such as carrier-to-noise ratio (CNR), composite second-order (CSO), composite triple beat (CTB), and bit error rate (BER), and the transmission performances of CATV/FTTH transport systems are limited by fiber dispersion effect in systems etc. To improve the overall performances of CATV/FTTH systems, it is necessary to employ some techniques or schemes in them [3, 4]. In this paper, an architecture of a down-link directly modulated CATV/FTTH transport system employing −1 side mode injection-locked and optoelectronic feedback techniques, as well as using a reflective semiconductor optical amplifier (RSOA) to remodulate the upstream FTTH signal, is proposed and experimentally demonstrated. A hybrid transport system that uses one optical channel to transit combined CATV and HTTH signals would be very useful for fiber links providing both CATV and FTTH services. With the help of −1 side mode injection-locked and optoelectronic feedback techniques, the resonance frequency of laser diode (LD) is enhanced greatly, resulting in significant improvements of overall performances. Moreover, RSOA, which has wavelength reuse and remodulation characteristics [5, 6], is expected to have good performances in down-link CATV/FTTH and up-link FTTH transport systems. Over a 50-km single-mode fiber (SMF) transmission, brilliant performances of CNR/CSO/CTB/BER were obtained for downlink transmission, and low BER value was achieved for up-link transmission.

2. EXPERIMENTAL SETUP

Figure 1 shows the experimental system configuration of our proposed RSOA-based down-link CATV/FTTH and up-link FTTH transport systems employing -1 side mode injection/optoelectronic feedback techniques. The solid line represents the optical signal path, and the dash line represents the electrical signal path. The transmitting signals including CATV and digital BB are combined using a RF combiner and applied to the distributed feedback (DFB) LD1. A total of 77 random phase continuous wave carriers from a multiple signal generator (MATRIX SX-16) were used to simulate analog CATV channels (channels 2–78, 55.25–547.25 MHz), and fed into the DFB LD1 (λ_1, 1548.25 nm) with an optical modulation index (OMI) of $\sim 3.5\%$ per channel. A data stream of 2.5 Gbps, with a pseudorandom binary sequence (PRBS) length of $2^{15} - 1$, was also supplied to the DFB LD1. The optical output of the DFB LD1 was injected into the DFB LD2 (λ_2, 1549.44 nm) via the optical circulator1 (OC1), with an injection power level of 3 dBm. For free-running, the DFB LD2 has an average output power of 0 dBm. With 3 dBm light injection, the DFB LD2 has a steady output power of about 3.2 dBm. The output of DFB

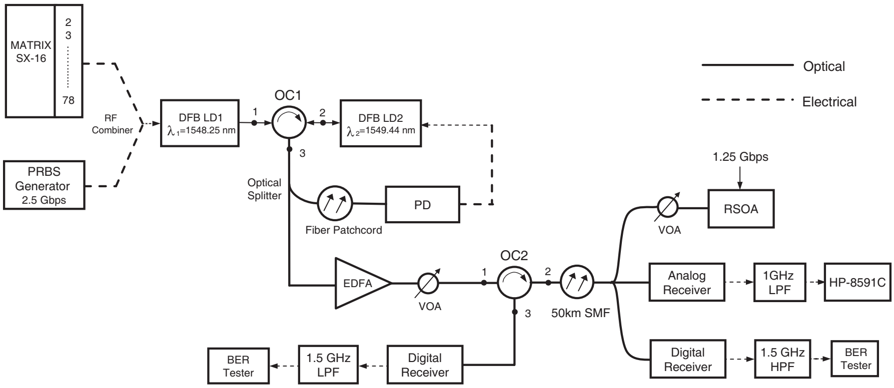

Figure 1. Experimental system configuration of our proposed RSOA-based down-link CATV/FTTH and up-link FTTH transport systems.

LD1 was coupled into the port 1 of OC1; the injection-locked DFB LD2 was coupled into the port 2 of OC1; the port 3 of OC1 was separated off by a 1×2 optical splitter. Part of the laser output was used for feedback through an optoelectronic feedback loop. The other part of the laser output was used for optical signal transmission. In the optoelectronic feedback loop, fiber span between the OC1 and photodiode (PD) is a fiber patchcord. The PD converts laser light into electrical signals to directly modulate the DFB LD2. The optoelectronic feedback loop optical power was amplified by erbium-doped fiber amplifier (EDFA) to transmit optical signal over a 50-km SMF transmission. The output power and noise figure of the EDFA are $\sim 17\,\mathrm{dBm}$ and $\sim 4.5\,\mathrm{dB}$, at an input power of 0 dBm, respectively. For optimum performance of the EDFA, the input optical power level needs to be kept at $0 \sim 3\,\mathrm{dBm}$. We place a variable optical attenuator (VOA) at the output of EDFA so that the optical power launched into the fiber is lower, then there would be a reduction in distortions. Over a 50-km SMF transmission (with an attenuation of 0.24 dB/km and a dispersion coefficient of 17 ps/nm/km), the received optical signal was separated by a 1×3 optical splitter. Part of the optical signal was detected by an analog optical receiver consisted of a broadband pin PD and an optical pre-amplifier, passed through a 1-GHz low-pass filter (LPF) to remove the distortions located above 1 GHz, and analyzed by a HP-8591C CATV analyzer. Another part of the optical signal was detected by a digital optical receiver consisted of a pin PD and an optical pre-amplifier, went through a 1.5-GHz high-pass filter (HPF), and was fed into a BER tester for BER analysis. Since 1.5 GHz HPF was available at our laboratory, while 2 GHz LPF was not available at our laboratory, we used a 1.5-GHz HPF to remove the distortions located below 1.5 GHz, instead of employing a 2-GHz LPF to remove the distortions located above 2 GHz. As to up-link transmission, a VOA is employed to adjust the RSOA seeding optical power. A RSOA with 1.25 Gbps data stream is placed at the receiving site to reuse the optical wavelength and remodulate the upstream data. No light source is needed for up-link transmission, leading to the reductions of complexity and cost. The optical signal was circulated by OC2 after being transmitted the same 50 km SMF link. The received optical signal was also detected by a digital optical receiver consisted of a pin PD and an optical pre-amplifier, went through a 1.5-GHz LPF to remove the distortions located above 1.5 GHz, and was fed into a BER tester for BER analysis.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

Nonlinear distortions (ϕ_{NL}) can be expressed as:

$$\phi_{NL} = (n_2/A_{eff}) \cdot L_{eff} \cdot P \tag{1}$$

where n_2 is the nonlinear refractive index; A_{eff} is the effective core area; L_{eff} is the effective fiber length; P is the optical power launched into the fiber. Since ϕ_{NL} is proportional to P, it is necessary to put a VOA at the output of EDFA to decrease the optical power launched into the fiber. Thus, there would be a reduction in distortions. The lower distortions are obtained, and the better transmission performances are achieved.

Figure 2 shows the measured side mode suppression ratio (SMSR) for the -1 side mode injection-locked (λ_{-1}, 1548.25 nm) of DFB LD2. One key feature of injection locking is that the injected laser is forced to oscillate at the injection frequency instead of the original free-running frequency. Therefore, the frequency component at the injection frequency becomes dominant. The injection locking behavior happens as an injection laser (DFB LD1) which is slightly detuned to wavelength longer than that of the injected laser (the -1 side mode of DFB LD2) [7]. As the -1 side mode of DFB LD2 (1548.23 nm) is injection-locked, its optical spectrum shifts a slightly longer wavelength (1548.25 nm), and the maximum SMSR value of 50 dB is obtained.

The resonance frequency of DFB LD2 for free-running, with 3 dBm $-$ 1 side mode injection, as well as with 3 dBm $-$ 1 side mode injection and optoelectronic feedback, are presented in Figure 3. For free-running, the resonance frequency of LD is around 5.4 GHz. With 3 dBm $-$ 1 side mode injection, the resonance frequency of LD

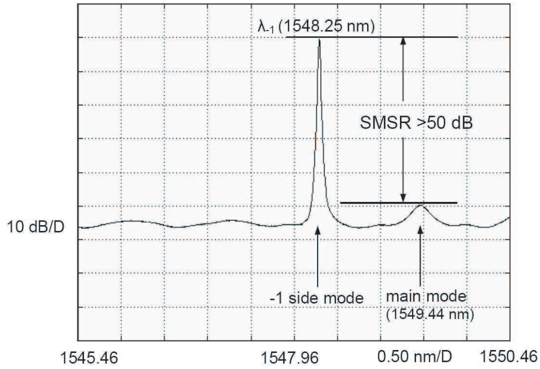

Figure 2. The measured SMSR for the -1 side mode injection-locked (λ_{-1}, 1548.25 nm) of DFB LD2.

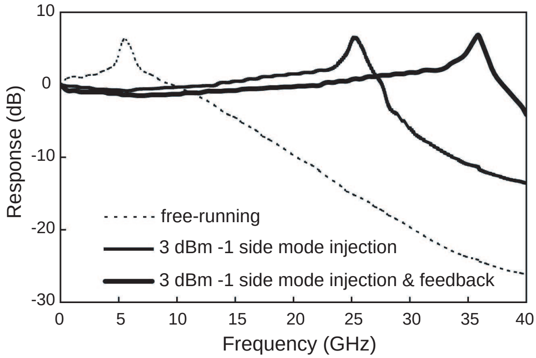

Figure 3. The resonance frequency of DFB LD2 for free-running, with 3 dBm−1 side mode injection, as well as with 3 dBm − 1 side mode injection and optoelectronic feedback.

is increased to 25 GHz. With 3 dBm − 1 side mode injection and optoelectronic feedback, the resonance frequency is increased up to 36 GHz. The optoelectronic feedback technique further enhances the resonance frequency of LD. Injection locking reduces LD threshold current, and optoelectronic feedback technique further suppresses it. The lower threshold current we get, the higher resonance frequency we obtain.

The gain model of SOA which explains the gain saturation phenomenon is given by:

$$G = \frac{P_{out}}{P_{in}} = \frac{G_0}{1 + P_{in}/P_{out}} \tag{2}$$

where G_0 is the unsaturated gain; P_{in} is the input optical power; P_{out} is the output optical power. To define the saturation optical power P_{sat}, at that power in which gain reducing to half of the G_0, the output power ($P_{R,out}$) and optical gain (G_R) of RSOA can be expressed as:

$$P_{R,out} = RG_R^2 P_{in} \tag{3}$$

$$G_R = \frac{-\left(P_{sat} + P_{in}\right) + \sqrt{\left(P_{sat} + P_{in}\right)^2 + 4RG_0 P_{sat} P_{in}}}{2RP_{in}} \tag{4}$$

where R is the reflectivity. It is obvious that, from Equations (4) and (5), the $P_{R,out}$ and G_R depend on the P_{in}; higher P_{in} leads to higher $P_{R,out}$ and lower G_R. Optical amplifier operating in lightwave transport systems must satisfy the stringent requirements on linearity. In bidirectional lightwave transport systems for up-link transmission, the RSOA cannot meet the demands as operated at high bias current because of gain saturation. The basic concept is to let RSOA to operate in the linear region, instead of the saturation region as this leads to distortions. The output power level of RSOA is presented in Figure 4 by sweeping the bias current at a constant seeding optical power $-25\,\text{dBm}$. As the bias current of RSOA is $< 60\,\text{mA}$, the RSOA is operated in the linear region. However, as the bias current of RSOA is $> 60\,\text{mA}$, the RSOA is operated in the saturation region. To optimize the up-link transmission performance, the RSOA is operated at a bias current of $45\,\text{mA}$, which is located at the linear region.

Figure 5(a) shows the measured CNR values under NTSC channel number for freerunning, with $3\,\text{dBm} - 1$ side mode injection, as well as with $3\,\text{dBm} - 1$ side mode injection and optoelectronic feedback, respectively. It is indicated that the CNR values ($\geq 50\,\text{dB}$) of these three systems are almost identical. The theoretical expression for CNR is:

$$\begin{aligned}\text{CNR} = \Big(&\text{CNR}_{\text{RIN}}^{-1} + \big(\text{CNR}_{\text{ASE}}^{-1} + \text{CNR}_{th}^{-1} + \text{CNR}_{shot}^{-1}\big) \\ &+ \Big(\text{CNR}_{sig\text{-}sp}^{-1} + \text{CNR}_{sp\text{-}sp}^{-1}\Big)\Big)^{-1}\end{aligned} \tag{5}$$

Each of the various CNR terms corresponds to a different element of the transmission system: CNR_{RIN} results from the LD relative intensity noise (RIN); CNR_{ASE} (due to amplifier spontaneous emission of optical pre-amplifier), CNR_{th} (due to thermal noise) and CNR_{shot} (due to shot noise) are associated with the optical receiver; $\text{CNR}_{sig\text{-}sp}$ (due to signal-spontaneous beat noise) and $\text{CNR}_{sp\text{-}sp}$ (due to spontaneous-spontaneous beat noise) are associated with the EDFA. Since CNR_{RIN}, (CNR_{ASE}+CNR_{th}+CNR_{shot}), and ($\text{CNR}_{sig\text{-}sp}$+$\text{CNR}_{sp\text{-}sp}$) of these

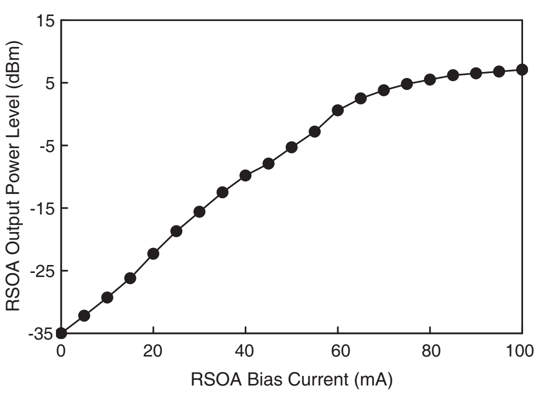

Figure 4. The output power level of RSOA by sweeping the bias current.

three systems are identical, causing that they have almost the same CNR values.

As to the CSO and CTB performances, as shown in Figures 5(b) and (c), the CSO and CTB values can be improved brilliantly by employing 3 dBm − 1 side mode injection and optoelectronic feedback techniques simultaneously. For free-running, the CSO/CTB values are 58.5/57.5 dB. With 3 dBm − 1 side mode injection, CSO/CTB enhancements of 4 dB (62.5/61.5 dB) have been achieved. With 3 dBm − 1 side mode injection and optoelectronic feedback, impressive

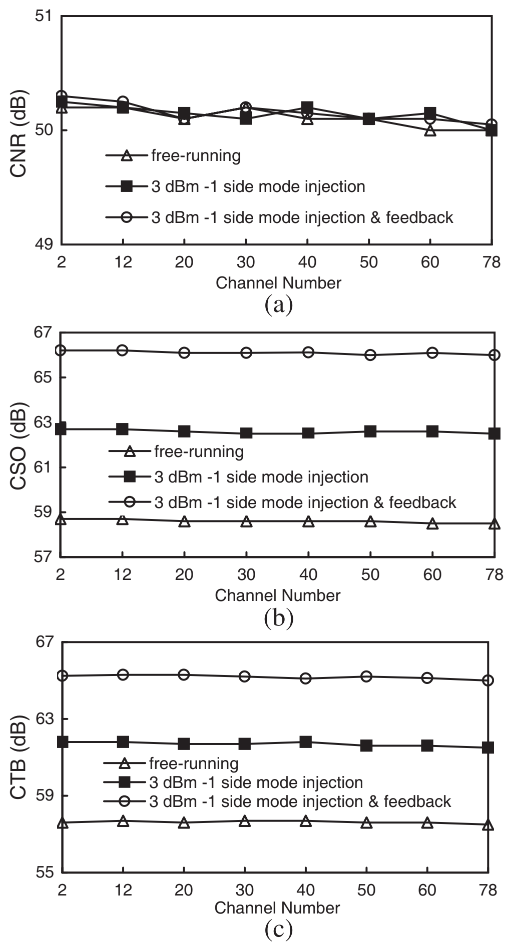

Figure 5. (a) The measured CNR values, (b) the measured CSO values, (c) the measured CTB values.

CSO/CTB enhancements of 7.5 dB (66/65 dB) have been obtained. The CSO/CTB distortions can be expressed as [8]:

$$\text{CSO} = 2HD + 10 \cdot \log N_{\text{CSO}} + 6\,(\text{dB}) \tag{6}$$

$$\text{CTB} = 3HD + 10 \cdot \log N_{\text{CTB}} + 6\,(\text{dB}) \tag{7}$$

where $2HD$ and $3HD$ are second- and third-order harmonic distortions; N_{CSO} and N_{CTB} are the product counts of CSO and CTB. The use of light injection and optoelectronic feedback techniques simultaneously increases the resonance frequency of LD, causing systems with lower $2HD$ and $3HD$. From Equations (6) and (7), it is obvious that to suppress $2HD/3HD$ greatly leads to significant CSO/CTB performance improvements.

High values of CNR, CSO and CTB are indeed required in analog AM-VSB CATV systems. With modern digital video broadcasting-cable (DVB-C) video transmission these requirements are much relaxed. In some countries, however, DVB-C video transmission systems are not implemented due to the high cost of head-end equipments. For the period to transfer the analog AM-VSB CATV systems into DVB-C video transmission ones, the analog AM-VSB CATV systems still play an important role to deliver the video programs to the subscribers. Thus, brilliant performances of CNR/CSO/CTB are still required, and these requirements are not much relaxed.

The measured down-link BER curves of 2.5 Gbps BB data channel are presented in Figure 6(a). At a BER of 10^{-9}, there exists a large power penalty of 8.6 dB between the back-to-back case and the free-running one due to fiber dispersion-induced penalty. At a BER of 10^{-9}, there exists a power penalty of 47 dB between the back-to-back case and the 3 dBm-1 sidemode injection one. And at a BER of 10^{-9}, there exists a little power penalty of 1.3 dB between the back-to-back case and the 3 dBm-1 sidemode injection/optoelectronic feedback one. The improvement results can be attributed to the fact that -1 sidemode light injection and optoelectronic feedback techniques significantly reduce the threshold current of DFB LD2 in which the optical output power of DFB LD2 is increased greatly. The higher optical power is launched into the fiber link, the better BER performance is obtained in systems. The down-link BER performance can be further improved by using a 2-GHz LPF to remove the high frequency distortions. More amplitude and jitter fluctuations can be removed by employing a 2-GHz LPF, resulting in systems with better BER performance.

And further, the measured up-link BER curves of 1.25 Gbps BB data channel are shown in Figure 6(b). To adjust the RSOA seeding powers to be -35, -30, -25, and -20 dBm, at a BER of 10^{-9} the corresponding received optical powers were -34, -36.7, -37.6, and

-37 dBm, respectively. Using a VOA to adjust the RSOA seeding power, the higher optical power is seeded into RSOA, the better BER performance is obtained in systems. While if RSOA seeding power is too high, the RSOA is operated in the gain saturation region, the BER performance will be degraded mainly from gain-saturation-induced nonlinear distortion. Therefore, for a RSOA used for up-link transmission, its seeding power P_s must be within the dynamic range of $P_{s,\min} \leq P_s \leq P_{s,\max}$, where $P_{s,\min}/P_{s,\max}$ is the minimum/maximum seeding power for RSOA to operate in the linear region. In addition,

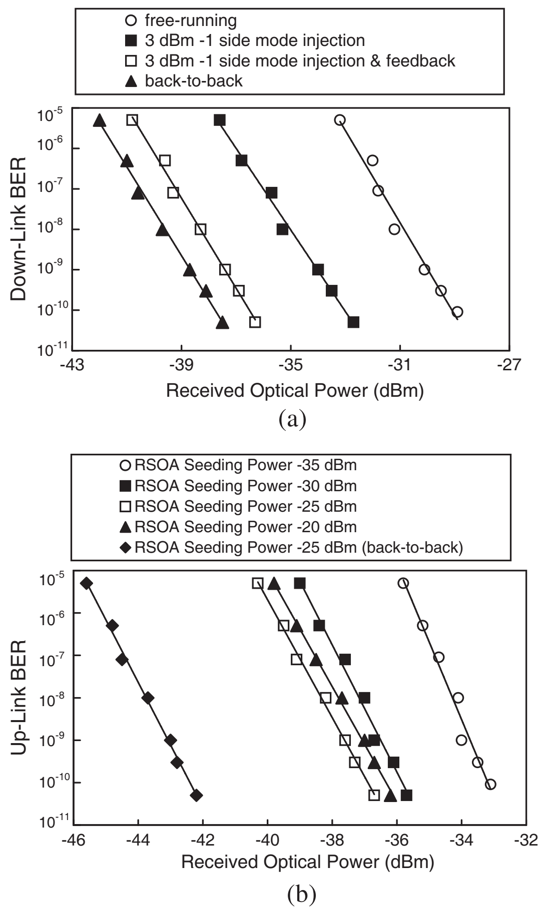

Figure 6. (a) The measured down-link BER curves of 2.5 Gbps BB data channel, (b) the measured up-link BER curves of 1.25 Gbps BB data channel.

the back-to-back BER curve as RSOA with -25 dBm seeding power is also given in Figure 6(b). At a BER of 10^{-9}, there exists a large power penalty of 9 dB between the back-to-back case and RSOA with -35 dBm seeding power penalty due to fiber dispersion-induced and low RSOA seeding power-induced penalties. And at a BER of 10^{-9}, there exists a power penalty of 5.4 dB between the back-to-back case and the RSOA with -25 dBm seeding power penalty due to fiber dispersion-induced penalty.

It is a transmission over a SMF using the same wavelength channel in both directions, it may happen that Rayleigh backscattering noise limits the systems seriously. The Rayleigh backscattering noise is generated due to both the back-reflection of downstream signal and that of remodulated upstream one in a RSOA. To reduce the Rayleigh backscattering noise caused by the remodulation, the RSOA is usually operated in the saturation region. Furthermore, the seeding signal of RSOA in this work consists of 2.5 Gbps data stream and analog CATV signals with the total power that varies in time. Thus, the RSOA modulates the reflected power and affects the 1,25 Gbps upstream data signal. However, the downstream signals are erased by the RSOA; with the elimination of the downstream signals, the upstream data is remodulated by the RSOA. Since the downstream signals are erased off clearly, the Rayleigh backscattering noise is caused by the remodulation; the amplitude variation is due to backscattering; the influence of the remodulation upstream data signal reaches the minimum values. Thereby, these degradation factors will not limit the systems seriously. If the RSOA is operated in the saturation region, then gain-saturation-induced distortion deteriorates the up-link transmission performance. For better performance of the up-link transmission, the RSOA is operated in the linear region, instead of gain saturation region.

4. CONCLUSION

A down-link CATV/FTTH and up-link FTTH transport system based on a RSOA as wavelength reuse and remodulation schemes is proposed and demonstrated. With the assistance of -1 side mode injection-locked/optoelectronic feedback techniques, impressive performances of downstream CNR/CSO/CTB/BER were obtained, and good performance of upstream BER value was achieved over a 50-km SMF transmission. The proposed system reveals an outstanding one with broadband access.

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