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# A BIDIRECTIONAL DIRECTLY MODULATED CABLE PON BASED ON A RSOA

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**Abstract**—A bidirectional directly modulated cable passive optical network (PON) based on a reflective semiconductor optical amplifier (RSOA) as a colorless modulator in the optical network unit (ONU) is proposed and demonstrated. Good performances of downstream carrier-to-noise ratio (CNR)/composite second-order (CSO)/composite triple beat (CTB) and upstream bit error rate (BER) were achieved over a 40-km single-mode fiber (SMF) transmission. This proposed directly modulated cable PON is simpler and cost lower than the externally modulated one.

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## 1. INTRODUCTION

Analog fiber optical CATV transport systems have recently been enhanced by the introduction of 1550 nm technology [1, 2]. CATV operators are increasingly competing with telecommunications carriers, and the winners in the long-term will be those service providers that build the infrastructure capacity to deliver broadband services. Cable passive optical network (PON), with CATV channel wavelength of 1550–1560 nm, allows cable providers to deliver deep-fiber services that simply plug directly into their existing cable infrastructures. The acceptable transmission performances of cable PON are limited by the parameters such as carrier-to-noise ratio (CNR), composite second-order (CSO), and composite triple beat (CTB). In the previous work, several methods have been proposed to improve the performances of fiber optical CATV systems. However, sophisticated sideband filtering technique [1], as well a expensive dual electrode Mach-Zehnder modulator (MZM) and phase modulator [3, 4] are required. Direct modulation of a distributed feedback laser diode (DFB LD) has therefore become attractive for lightwave transport systems, because it costs lower compared with an externally modulated transmitter. In recent studies, reflective semiconductor optical amplifier (RSOA) has been used as wavelength reuse and remodulation schemes in bidirectional wavelength-division-multiplexing PON and radio-over-fiber transport systems [5, 6]. But, its application in a bidirectional directly modulated cable PON has not been reported. RSOA-based optical network unit (ONU) configuration is capable of providing colorless cable PON operation, thus expecting to have good performances in a bidirectional directly modulated cable PON. In this paper, an architecture of a bidirectional directly modulated cable PON based on a RSOA as a colorless modulator in the ONU is proposed and demonstrated. With the help of injection locking technique, good performances of downstream CNR/CSO/CTB and upstream bit error rate (BER) were obtained over a 40-km single-mode fiber (SMF) transmission.

## 2. EXPERIMENTAL SETUP

Figure 1 shows two bidirectional transmission cable PON employing a RSOA as a colorless modulator in the ONU. Figure 1(a) (referred to as system I) shows the bidirectional externally modulated cable PON. Figure 1(b) (referred to as system II) shows our proposed bidirectional directly modulated cable PON. The output power and noise figure of erbium-doped fiber amplifier (EDFA) used in systems I and II are

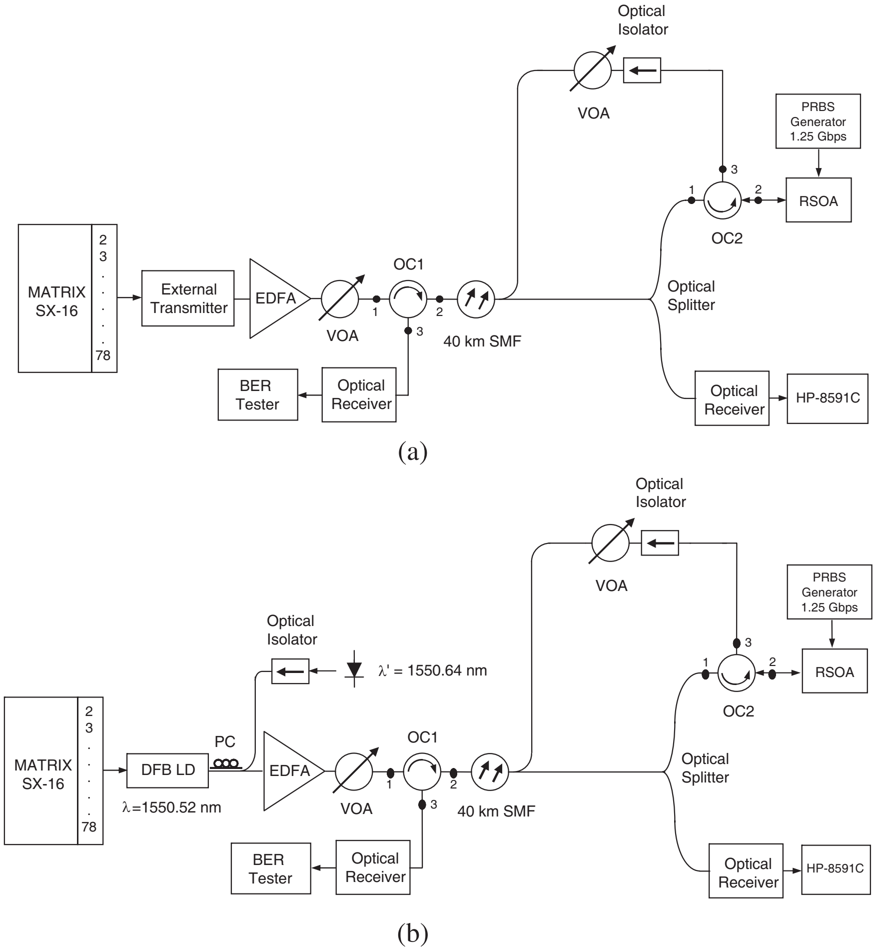


**Figure 1.** (a) The bidirectional externally modulated cable PON based on a RSOA. (b) Our proposed bidirectional directly modulated cable PON based on a RSOA.

$\sim$ 17 dBm and $\sim$ 4.5 dB, at an input power of 0 dBm, respectively. In system I, channels 2–78 generated from a multiple signal generator (MATRIX SX-16) were fed into an externally modulated transmitter with an optical modulation index (OMI) of $\sim$ 3.5% per channel. In system II, a total of 77 carriers (30 dBmV per carrier) from a multiple signal generator were directly fed into the DFB LD, with a central wavelength of 1550.52 nm ($\lambda$) and an OMI of 3.5% per channel. Light is injected in the counter-propagation direction through an optical isolator, an optical coupler, and a polarization controller. To transmit optical signal over a 40-km SMF link, the optical power was amplified by an EDFA. The variable optical attenuator (VOA) was introduced at the start of the optical link, this would have resulted in less distortions since the optical power launched into the fiber would have been less, and the optical power seeded into the RSOA would have been optimized. Next to the VOA, an optical circulator (OC1) was placed to bridge both downstream and upstream signals. Over a 40-km SMF transmission, the downstream signal was split by a $1 \times 2$ optical splitter. One half of the signal was received by an analog optical receiver; while the other half was reused, remodulated, and circulated by RSOA and OC2. All CATV parameters of CNR, CSO and CTB were measured and analyzed in the ONU by an HP-8591C CATV analyzer.

As to up-link transmission, a RSOA with 1.5 GHz modulation bandwidth was placed in the ONU as a colorless modulator. The downstream optical signal was directly modulated through a RSOA by a 1.25-Gbps upstream data signal, with a pseudorandom binary sequence (PRBS) length of $2^{15} - 1$. The optical signal was circulated and attenuated by OC2 and VOA, before coupled into the same 40 km SMF link. Since both of the downstream and upstream signals were transmitted at the same SMF, an optical isolator was placed next to the OC2 to avoid the downstream signal. Over a 40-km SMF transmission, the optical signal was circulated by the OC1, detected by a digital optical receiver, and fed into to a BER tester for BER performance analysis.

## 3. EXPERIMENTAL RESULTS AND DISCUSSIONS

Injection locking scheme is employed in system II, the injection locking has been taken place as the frequency of slave laser is locked nearly that of the master laser. The half locking range of an injection-locked LD is expressed as [7]:

$$\Delta\nu = \frac{1-R}{2\pi\tau_p}\sqrt{1+\alpha^2}\sqrt{\frac{P_m}{P_s}} \tag{1}$$

where $R$ is the slave laser top-mirror reflectivity, $\tau_p$ is the photon lifetime in the slave laser, $\alpha$ is the linewidth enhancement factor of the slave laser, $P_m$ denote the optical power of the master laser coupled into the slave laser, and $P_s$ is the optical power of the free-running slave laser. An optimum injection locking can be achieved if the frequency of the master laser is lower than the free-running slave laser frequency, i.e., negative detuning. Within the locking range, the frequency of slave laser is locked nearly to the frequency of master laser. However, outside the locking range, severe oscillation occurs. When a DFB LD is injection-locked, its optical spectrum shifts a slightly longer wavelength (0.12 nm), matching to that of $\lambda'$, and becomes narrower in linewidth. The injection locking behavior happens when an injection source laser is slightly detuned to frequency (14.23 GHz) lower than that of the injection-locked LD. The optimal injection locking condition is found when the detuning between $\lambda'$ and $\lambda$ is $+0.12$ nm or $-14.23$ GHz. As the detuning is $-14.23$ GHz, system has the best transmission performance in terms of the lowest threshold current of slave laser (DFB LD), the highest CNR/CSO/CTB values, the lowest received optical power level (as BER is $10^{-9}$), and the minimum amplitude and jitter fluctuations in the eye diagram.

It is a transmission over a SMF using the same wavelengths 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 signal in a RSOA. To reduce the Rayleigh backscattering noise caused by the remodulation, the RSOA is operated in the saturation region. Figure 2 shows the measured BER values for up-link transmission by varying the RSOA input power level from $-30$ to $-10$ dBm; in other words, from the linear region to the saturation one. As the RSOA input power was increased, the reflection

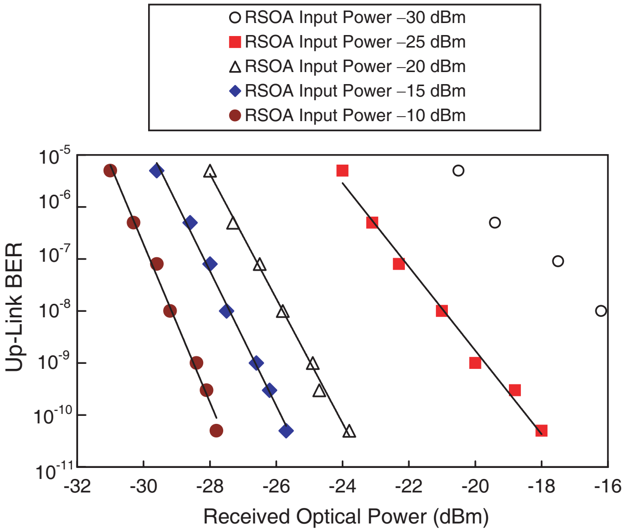
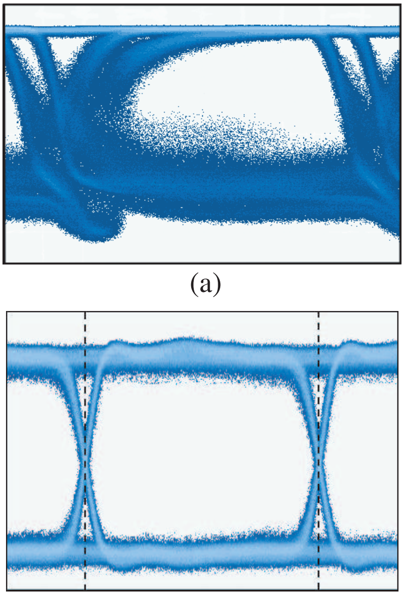


**Figure 2.** The measured BER values for up-link transmission by varying the RSOA input power level from $-30$ to $-10$ dBm.

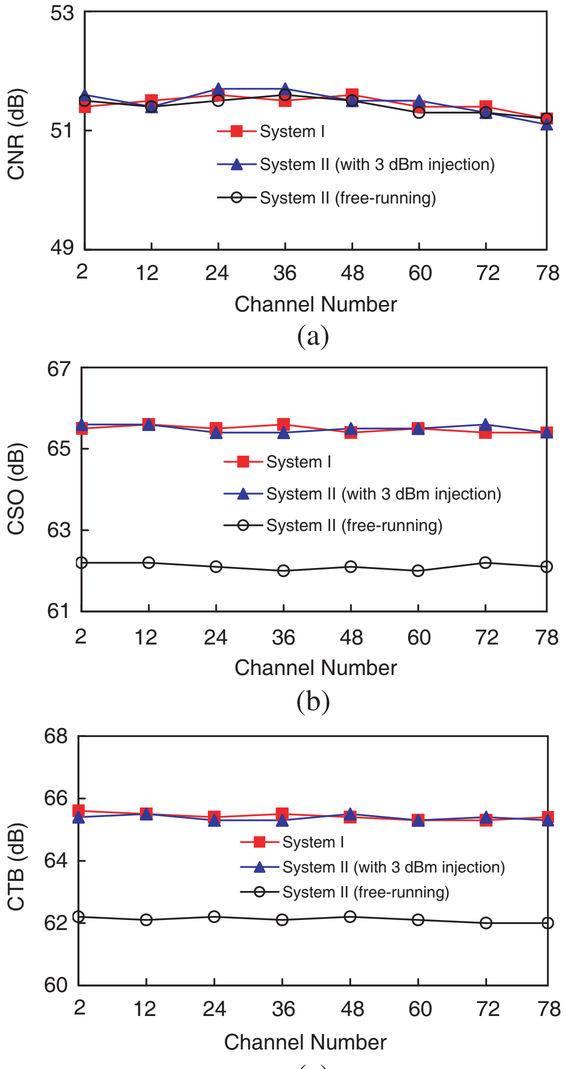
tolerances of both the downstream and upstream signals were improved to some extent. This was mainly due to the fact that the RSOA gain was reduced as the injection power increased, and consequently the power ratio of the reflected light to the signal light was reduced. The higher the input power into the RSOA, the more suppressed the downstream signal in the upstream transmission become, finally improved the BER performance of upstream data signal.

The eye diagrams corresponding to the RSOA input power levels of $-30$ and $-10\,\mathrm{dBm}$ are demonstrated in Figures 3(a) and (b), respectively. Amplitude and jitter fluctuations in the signal are clearly observed in Figure 3(a). Originally, the downstream CATV signal should be erased by the RSOA. With the elimination of the downstream CATV signal, the upstream data signal is remodulated by the RSOA. Nevertheless, the downstream CATV signal is not sufficiently suppressed since the RSOA is operated in the linear region, leading to fluctuations in eye diagram. In Figure 3(b), amplitude and jitter fluctuations in the signal are clearly reduced due to the sufficient suppression of the downstream CATV signal.


(a)

(b)

**Figure 3.** (a) The eye diagram corresponding to the RSOA input power level of $-30\,\mathrm{dBm}$. (b) The eye diagram corresponding to the RSOA input power level of $-10\,\mathrm{dBm}$.



(a)

(b)

(c)

**Figure 4.** (a) The measured CNR values as RSOA with −10 dBm input power under NTSC channel number for systems I and II. (b) The measured CSO values as RSOA with −10 dBm input power under NTSC channel number for systems I and II. (c) The measured CTB values as RSOA with −10 dBm input power under NTSC channel number for systems I and II.

Figures 4(a), (b) and (c) show the measured CNR, CSO and CTB values as RSOA with −10 dBm input power under NTSC channel number for systems I and II, respectively. Since CNR value results from the relative intensity noise of LD, thermal and shot noise of optical receiver, as well as signal-spontaneous and spontaneous-spontaneous beat noise of EDFA; CNR values ($\geq$ 51 dB) of systems I and II (with 3 dBm injection and free-running) are almost identical due to the use of an identical LD, same input optical power levels of EDFA and optical receiver. As to CSO/CTB performances, the CSO/CTB values of system II are improved from $\geq$ 62/62 dB (free-running) to $\geq$ 65.4/65.3 dB (with 3 dBm injection). The improved results can be attributed to the use of injection locking technique to reduce the laser frequency chirp; and the limited transmission distance to suppress the distortions induced from frequency chirp in combination with fiber dispersion. The laser frequency chirp can be reduced as the wavelength of the modulated laser is injection-locked. The corresponding phase $\theta$ of the laser under light injection is given by [8]:

$$\frac{d\theta}{dt} = \gamma \left\{ 2\pi \cdot \tau_p \cdot d - \frac{\alpha}{2}(n_{th} \cdot g - 1) - \frac{\tau_p}{T} \left( \frac{S_i}{S} \right)^{1/2} \cdot \sin\theta \right\} \tag{2}$$

where $\gamma$ is the ratio between the electron and photon lifetimes, $d$ is the frequency detuning, $n_{th}$ is the normalized carrier density, $g$ is the gain coefficient, $T$ is the cavity roundtrip time, and $\frac{S_i}{S}$ is the injection ratio. Since chirp is related to deviations of the phase of the optical field, it is clear from Equation (2), a reduction of chirp can be obtained by an injection locking. Moreover, system link with a transmission length of 40 km SMF has a low fiber dispersion; thereby, distortions induced from frequency chirp combined with fiber dispersion can be suppressed.

## 4. CONCLUSION

A bidirectional directly modulated cable PON employing a RSOA as a colorless modulator in the ONU is proposed and demonstrated. Good performances of downstream CNR/CSO/CTB and upstream BER were obtained. It reveals a prominent one with simpler and more economic advantages than that of externally modulated cable PON.

## ACKNOWLEDGMENT

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