Progress In Electromagnetics Research Letters, Vol. 11, 73–82, 2009

DIRECT MODULATION WITH SIDE-MODE INJECTION IN OPTICAL CATV TRANSPORT SYSTEMS

W.-J. Ho, H.-H. Lu, C.-H. Chang, W.-Y. Lin, and H.-S. Su

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

Abstract—A split-band directly modulated fiber optical CATV system employing -1 side-mode injection-locked and semiconductor optical amplifier (SOA)-based optical single sideband (SSB) modulation techniques is proposed and experimentally demonstrated. For our proposed systems, it is relatively simple to implement as only one SOA is required. Excellent performances of carrier-to-noise ratio (CNR), composite second order (CSO), and composite triple beat (CTB) were achieved over a 100-km single-mode fiber (SMF) transmission.

1. INTRODUCTION

Distributed feedback laser diode (DFB LD) with direct modulation can be employed for transmitting CATV signals at very low cost compared to externally modulated fiber optical CATV systems. However, nonlinear distortions occur greatly when DFB LD is directly modulated with analog signals, and these distortions will cause severe system performance degradations. To reduce distortions generated from directly modulated systems, Meng et al. have reported that they can be suppressed with main mode optical injection locking [1]. In addition, side-mode injection-locked technique for greater distortions suppression has been proposed [2, 3]. And further, low fiber dispersion is necessary for analog optical links to get good transmission performances. Optical single sideband (SSB) modulation technique is an effective approach to overcome the fiber dispersion since the optical linewidth is reduced by a factor of two. Several approaches have been proposed to generate optical SSB signal. But, sophisticated sideband filtering technique [4], expensive dual electrode

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

Mach-Zehnder modulator (MZM) and phase modulator [5, 6] are required. In this paper a directly modulated fiber optical CATV system employing −1 side-mode injection-locked and semiconductor optical amplifier (SOA)-based optical SSB modulation techniques is proposed and experimentally demonstrated. This proposed approach is relatively simple to implement, as it requires only one SOA. Additional sophisticated technique or expensive optical devices are not required. Over a 100-km single-mode fiber (SMF) transmission, excellent performances of carrier-to-noise ratio (CNR), composite second order (CSO), and composite triple beat (CTB) were obtained in our proposed systems.

2. EXPERIMENTAL SETUP

The experimental configuration of our proposed split-band directly modulated fiber optical CATV systems employing DFB LDs with −1 side-mode injection-locked and SOA-based optical SSB modulation techniques is shown in Figure 1. A multiple signal generator (Matrix SX-16) is used to simulate analog CATV channels (channels 2–78).

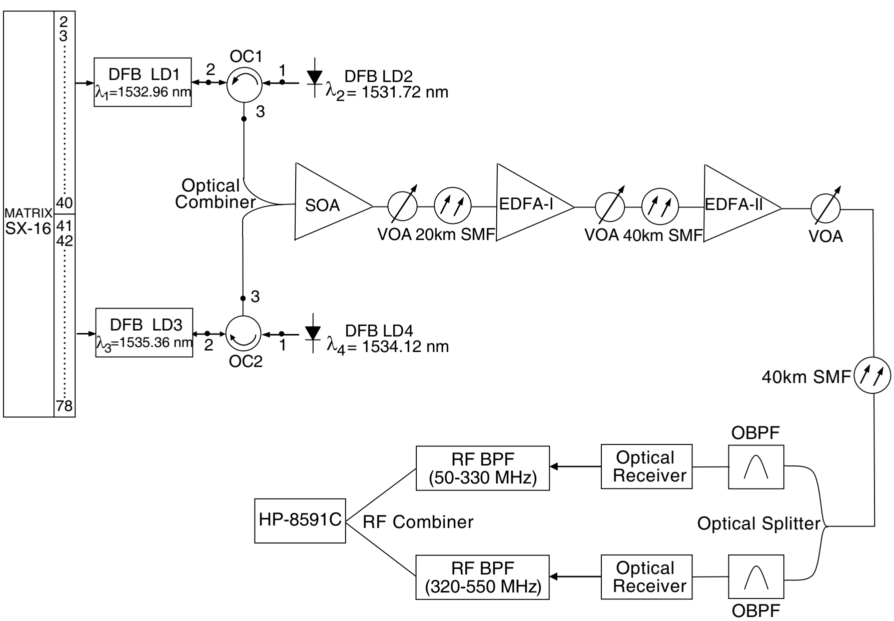

Figure 1. Experimental configuration of our proposed split-band directly modulated fiber optical CATV systems.

A total of 77 RF sub-carriers from the Matrix SX-16 were fed into two directly modulated DFB LDs with an optical modulation index (OMI) of $\sim$ 3.6% per channel. Large OMI results in better CNR performance but degrades the CSO/CTB performance. In order to satisfy the CATV requirements, the OMI value needs to be set at an optimum value. Channels 2–40 are directly fed into DFB LD1 (λ_1, 1532.96 nm), and channels 41–78 are directly fed into DFB LD3 (λ_3, 1535.36 nm). The optical output of the DFB LD2 (λ_2, 1531.72 nm) was injected into the DFB LD1 via the optical circulator1 (OC1), with an injection power level of -3 dBm. Meanwhile, the optical output of the DFB LD4 (λ_4, 1534.12 nm) was injected into the DFB LD3 via the OC2, with an injection power level of -3 dBm. The optical powers of injection-locked LD1 and LD3 were coupled into the SOA by a 2×1 optical combiner to generate optical SSB signals. The optical signals are transmitted through three SMF spans ($20 + 40 + 40$ km) with the help of one SOA and two erbium-doped fiber amplifiers (EDFAs). We place a variable optical attenuator (VOA) at the start of each optical link so that the optical power launched into the fiber is lower. Over a 100-km SMF transmission, the received optical signals were split by a 1×2 optical splitter, went through two separate optical band-pass filters (OBPFs) to select the appropriate wavelength, detected using two optical receivers, passed through two separate RF BPFs (50–330 and 320–550 MHz) to remove the spurious, and recombined the RF signals using a 2×1 RF combiner. CNR, CSO and CTB values were measured using an HP-8591C CATV analyzer over a 100-km SMF transmission.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

The resonance frequency f_0 in an injection-locked laser can be stated as [7]

$$f_0 \approx \frac{1}{2\pi}\left(\frac{F_a G_a G_{a,n}}{\Gamma} - \frac{f^2 F_I}{4F_a}\right)^{1/2} \tag{1}$$

where F_a and F_I are the average photon densities of the mode a, and of the injected light, G_a is the modal gain of the mode a; $G_{a,n} = dG_a/dn$; f is the intermodal spacing in the frequency domain. f_0 is enhanced with injection into negative mode greatly; it means that -1 side-mode injection-locked technique lets systems' performance improve significantly. The frequency response of DFB LD1 for free-running, with -3 dBm main mode injection, as well as with -3 dBm -1 side-mode injection, is present in Figure 2. In the free-running case, the laser resonance frequency is around 5.2 GHz. With -3 dBm

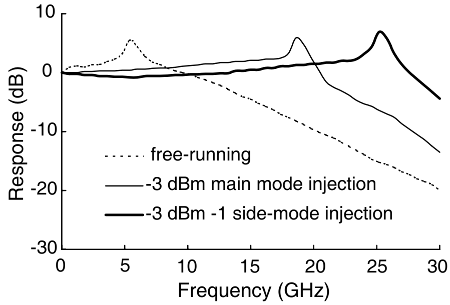

Figure 2. The frequency response of DFB LD1 for free-running, with -3 dBm main mode injection, as well as with -3 dBm -1 side-mode injection.

main mode injection, the laser has a resonance frequency of about 18.3 GHz. With -3 dBm -1 side-mode injection; the laser resonance frequency is increased significantly to 25.2 GHz, which is more than 4.85 times ($25.2/5.2 \sim 4.85$) laser resonance frequency of free-running case. With light injection, because of the coherent summation of externally injected and internally generated slave fields, the phase adds an additional dynamic variable. Consequently, a new resonant coupling between the field amplitude and phase appears and can dominate the laser resonance frequency.

One key feature of injection locking is that the injected laser (slave laser) is forced to oscillate at the injection frequency. Therefore, the frequency component at the injection frequency becomes dominant. The injection locking behavior happens when an injection laser (master laser) is slightly detuned to frequency lower than that of the injected laser, i.e., negative frequency detuning is employed to achieve an injection locking [8]. As the -1 side-mode of DFB LD2 and LD4 are injection-locked, their -1 side-mode optical spectra shift a slightly longer wavelength (1531.72 and 1534.12 nm).

Figure 3(a) shows the optical DSB-modulated signals, with central wavelengths of 1531.72 and 1534.12 nm, in an optical spectrum analyzer (OSA) at the SOA output. The optical DSB signal is obtained as the SOA input optical power is 0 dBm per wavelength. However, Figures 3(b) and (c) show the optical SSB-modulated signals in an OSA at the SOA output. The optical SSB signals are obtained as the SOA input optical powers are -5 and -8 dBm per wavelength, respectively. When the optical DSB signal was coupled into the SOA at the input power of $-5 \sim -8$ dBm per wavelength, there was a large change in the optical signals at the SOA output. The amplitude of

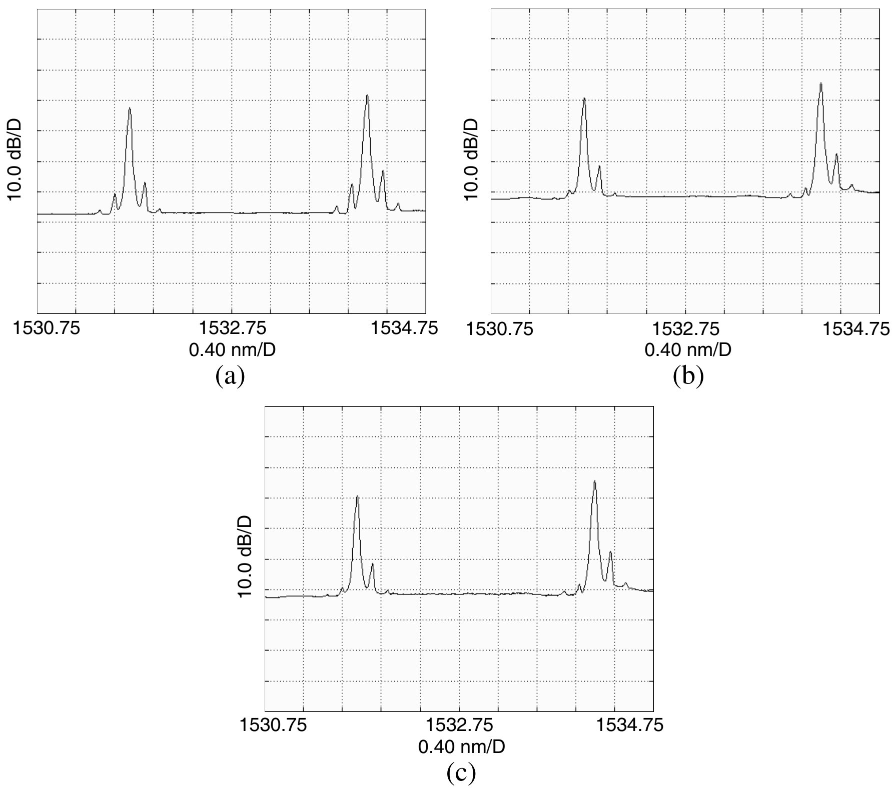

Figure 3. (a) The optical DSB-modulated signals (1531.72 nm, λ_2) and (1534.12 nm, λ_4) at the SOA output (SOA input optical power is 0 dBm per wavelength). (b) The optical SSB-modulated signals at the SOA output (SOA input optical power is -5 dBm per wavelength). (c) The optical SSB-modulated signals at the SOA output (SOA input optical power is -8 dBm per wavelength).

the optical sideband at the right-hand side of the optical carrier was not changed, but the amplitude of the optical sideband at the left-hand side of the optical carrier was suppressed, i.e., the optical SSB signal was created. In this proposed systems, optical SSB signal was created and transmitted as the SOA input optical power was -5 dBm per wavelength (λ_2 and λ_4).

Considering both self-phase modulation and self-gain modulation in the SOA, the electrical field of the output signal in an SOA can be expressed as

$$E(t)=E_0\left[1+\frac{m}{2}\sin(\omega_m t)\right]\cdot\exp\left[i\omega_0 t+(1+i\alpha)\frac{m}{2}\eta P_{eff}\sin(\omega_m t+\beta)\right] \quad (2)$$

where E_0 is the output carrier amplitude; m is the input signal modulation index; ω_m is the subcarrier frequency; ω_0 is the optical carrier frequency; α is the linewidth enhancement factor; η is a coefficient that depends on the gain feature of the SOA; P_{eff} is the effective input optical power; β is the phase difference between the change of carrier density and change of input optical power. Expanding Equation (2) in Bessel series and neglecting high-order terms, the complex envelopes for the frequencies $\omega_0 + \omega_m$ (upper sideband) and $\omega_0 - \omega_m$ (lower sideband) can be estimated as:

$$E^{\omega_0\pm\omega_m} \approx \mp\frac{im}{4}E_0 J_0(\chi)\cdot\{1+\rho\exp[j(\theta\pm\beta)]\} \quad (3)$$

where $\theta = \tan^{-1}\alpha$, $\rho = \eta P_{eff}(1+\alpha^2)^{1/2}$, and $\chi = \frac{-im\rho\exp(i\theta)}{2}$.

Then sideband suppression ratio (SSR) can be derived:

$$SSR = \left|\frac{E^{\omega_0-\omega_m}}{E^{\omega_0+\omega_m}}\right|^2 \approx \left|\frac{1+\rho\exp[j(\theta-\beta)]}{1-\rho\exp[j(\theta+\beta-\pi)}\right|^2 \quad (4)$$

ρ is adjustable as a function of input optical power. Thereby, as

$$\rho\cos(\theta+\beta-\pi)=1 \quad (5)$$

the maximum SSR can be obtained. The power level differences between the carrier and upper sideband for λ_4 at the SOA output at different input optical powers per wavelength are given in Table 1. It can be seen that the power level differences of 26–34 dB are achieved. As optimal optical powers are launched (−5 dBm per wavelength), the maximum power level difference of 34 dB is obtained. Under this condition, it corresponds to Equation (4) as denominator is approached to zero.

Figure 4(a) shows the measured CNR values under NTSC channel number for free-running, with −3 dBm −1 side-mode injection and optical DSB-modulated, as well as with −3 dBm −1 side mode injection and SOA-based optical SSB-modulated, respectively. It can be seen that the CNR value is increased as −3 dBm optical power is injected into the slave laser. The CNR value depends critically on the optical input power; as the power injected into the salve laser is increased, the power launched into the EDFA is increased. The higher optical power is launched into the EDFA, the better CNR performance is

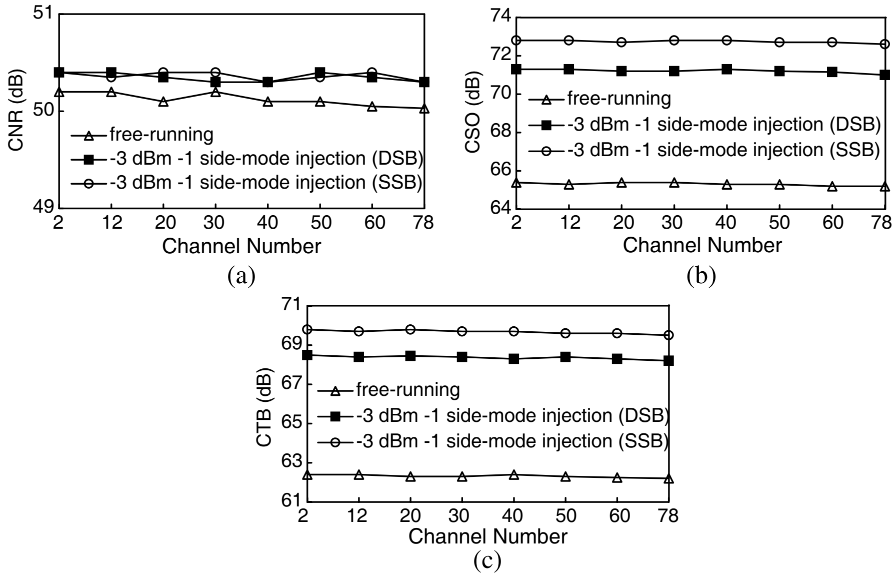

Figure 4. (a) Measured CNR values. (b) Measured CSO values. (c) Measured CTB values.

Table 1. The power level differences between the carrier and the upper sideband for λ_4 at the SOA output at different input optical powers per wavelength.

Input Optical Power (dBm)	Power Level Difference (dB)
-3	28
-4	30.7
-5	34
-6	33.7
-7	33.3
-8	33
-9	31.2
-10	29.8
-11	28.2
-12	27.3
-13	26

obtained in systems. As to the CSO and CTB performances, as shown in Figures 4(b) and (c), the CSO and CTB values can be improved significantly by employing -1 side-mode injection-locked and SOA-based optical SSB-modulated techniques. In the free-running case, the CSO/CTB values ($> 65/62$ dB) meet the fiber optical CATV demands ($> 65/60$ dB) due to the use of split-band scheme. With -3 dBm -1 side mode injection and optical DSB-modulated, CSO/CTB improvements of ~ 6 dB ($> 71/68$ dB) have been achieved. With -3 dBm -1 side-mode injection and SOA-based optical SSB-modulated, large CSO/CTB improvements of ~ 7.5 dB ($> 72.6/69.5$ dB) have been achieved. The improvements are from the use of -1 side mode injection-locked technique to increase the laser resonance frequency greatly and SOA-based optical SSB modulation one to overcome the fiber dispersion significantly. Second-order intermodulation suppression (IMS_2) and third order intermodulation suppression (IMS_3) can be expressed as

$$IMS_2 \cong 10\log\left\{m\frac{(f/f_0)^2}{g(2f)}\right\} \tag{6}$$

$$IMS_3 \cong 10\log\left\{\frac{m^2}{2}\frac{(f/f_0)^4 - \frac{1}{2}(f/f_0)^2}{g(f)g(2f)}\right\} \tag{7}$$

where $g(f)$ is the gain of the laser medium as a function of frequency. Both IMS_2 and IMS_3 values can be very small as $f \ll f_0$. Since f is in the CATV band (55–550 MHz), far from the f_0 (25.2 GHz; with -3 dBm -1 side-mode injection), both IMS_2 and IMS_3 values become very small. The use of -1 side-mode injection locking technique greatly increases the laser resonance frequency, resulting in system with lower IMS_2 and IMS_3, leading to improvements of CSO and CTB performances.

In addition, the CSO and CTB distortions are given by [9]

$$CSO = 20\cdot\log\left[\sqrt{N_{CSO}}\frac{\left[\frac{dG(P,\lambda)}{d\lambda}\right]\Delta\lambda}{2G(P,\lambda)}\right] \tag{8}$$

$$CTB = 20\cdot\log\left[\sqrt{N_{CTB}}\frac{\left[\frac{d^2G(P,\lambda)}{d\lambda^2}\right]\Delta\lambda^2}{4G(P,\lambda)}\right] \tag{9}$$

where $N_{CSO(CTB)}$ is the product count of second (third) order intermodulation; $G(P,\lambda)$ is the gain of the EDFA; $dG(P,\lambda)/d\lambda$ is the gain tilt of the EDFA; $\Delta\lambda$ is the spectral width of the optical signal. The use of SOA-based optical SSB modulation technique lets the spectral linewidth change from a broad linewidth into a narrow one, resulting in lower fiber dispersion. Then, there would be significant reductions in CSO and CTB distortions.

4. CONCLUSION

We proposed and experimentally demonstrated a split-band directly modulated fiber optical CATV system employing −1 side-mode injection-locked and SOA-based optical SSB modulation techniques. Our proposed scheme is relatively easy to implement, as only one SOA is required. Excellent performances of CNR, CSO and CTB were achieved over a 100-km SMF transmission.

ACKNOWLEDGMENT

The authors would like to thank the financial support from the National Science Council of the Republic of China under Grant NSC 98-2221-E-027-008, NSC 98-2622-E-027-010-CC3, and NSC 97-2221-E-027-008-MY2.

REFERENCES

1. Meng, X. J., T. Chau, and M. C. Wu, "Improved intrinsic dynamic distortions in directly modulated semiconductor lasers by optical injection locking," *IEEE Trans. Microwave Theory and Tech.*, Vol. 47, 1172–1176, 1999.
2. Lu, H.-H., C.-Y. Li, C.-H. Lee, Y.-C. Hsiao, and H.-W. Chen, "Radio-over-fiber transport systems based on DFB Ld with main and −1 side modes injection-locked technique," *Progress In Electromagnetics Research Letters*, Vol. 7, 25–33, 2009.
3. Seo, J. H., Y. K. Seo, and W. Y. Choi, "Nonlinear distortion suppression in directly modulated distributed feedback lasers by sidemode optical injection locking," *Jpn. J. Appl. Phys.*, Vol. 41, L136–L138, 2002.
4. Tzeng, S.-J., H.-H. Lu, C.-Y. Li, K.-H. Chang, and C.-H. Lee, "Cso/Ctb performance improvement by using Fabry-Perot etalon at the receiving site," *Progress In Electromagnetics Research Letters*, Vol. 6, 107–113, 2009.
5. Davies, B. and J. Conrad, "Hybrid modulator structure for subcarrier and harmonic subcarrier optical single sideband," *IEEE Photon. Technol. Lett.*, Vol. 10, 600–602, 1998.

6. Lee, U. S., H. D. Jung, and S. K. Han, "Optical single sideband signal generation using phase modulation of semiconductor optical amplifier," *IEEE Photon. Technol. Lett.*, Vol. 16, 1373–1375, 2004.
7. Hong, Y. and K. A. Shore, "Locking characteristics of a side-mode injected semiconductor laser," *IEEE J. Quantum Electron.*, Vol. 35, 1713–1717, 1999.
8. Chang, C. H., L. Chrostowski, C. J. Chang-Hasnain, and W. W. Chow, "Study of long-wavelength VCSEl-VCSEL injection locking for 2.5-Gb/s transmission," *IEEE Photon. Technol. Lett.*, Vol. 14, 1635–1637, 2002.
9. Clesca, B., P. Bousselet, and L. Hamon, "Second-order distortion improvements or degradations brought by Erbium-doped fiber amplifiers in analog links using directly modulated lasers," *IEEE Photon Technol. Lett.*, Vol. 5, 1029–1031, 1993.