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FIBER-TO-THE-HOME INTEGRATION WITH DIGITAL LINK ON MICROWAVE SUBCARRIER TRANSPORT SYSTEMS

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Abstract—A directly modulated fiber-to-the-home (FTTH) integration with digital link on microwave subcarrier (DLOMS) transport system based on −1 side mode injection-locked and optoelectronic feedback techniques is proposed and demonstrated. Directly modulated baseband (BB) (622 Mbps) and radio frequency (RF) (622 Mbps/10 GHz) signals are successfully transmitted simultaneously over an 80-km standard single-mode fiber (SMF) transmission. Low bit error rate (BER) values and clear eye diagrams were achieved in our proposed systems. This demonstrated FTTH/DLOMS transport system is a promising candidate for broadband access networks.

1. INTRODUCTION

The landscape of communications is now undergoing a large change. Over the last decade the world has seen a great transformation in communications. It is well known that there are various technology options for broadband access networks providing high-speed internet access and triple-play services including data, voice, and video. It is in general agreed that fiber-to-the-home (FTTH) and digital link on microwave subcarrier (DLOMS) provide the ultimate in bandwidth and flexibility in upgrades when considering really high-speed broadband access, especially with data rate of 100 Mbps to 1.25 Gbps [1–4]. FTTH integrating with DLOMS transport systems have provided a way to transmit baseband (BB) and radio frequency (RF) signals simultaneously. Nevertheless, the overall transmission performances of FTTH/DLOMS transport systems are limited by the problem

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such as signal fading due to fiber dispersion [5]. Thereby, it is necessary to take some ways to overcome signal fading problem and reduce fiber dispersion when transmitting BB and RF signals simultaneously. The feasibility of employing one Fabry-Perot laser diode (FP LD) with two modes injection-locked to transmit BB and RF signals simultaneously was demonstrated previously [6]. However, the architecture of systems can be further simplified by combining BB and RF signals in electrical domain first and direct modulating distributed feedback (DFB) LD. In addition, the system performance can be further improved by using -1 side mode injection-locked and optoelectronic feedback techniques [7]. In this paper, a directly modulated FTTH/DLOMS transport system based on -1 side mode injection-locked and optoelectronic feedback techniques is proposed and demonstrated. In previous studies [8, 9], DFB LD with light injection and optoelectronic feedback techniques has been proposed in analog CATV/radio-over-fiber (ROF) transport systems to enhance the transmission performance of systems. However, DFB LD with light injection and optoelectronic feedback techniques in practical implementation of directly modulated FTTH/DLOMS transport systems has not been proposed. To the best of our knowledge, it is the first time to transmit digital and analog signals simultaneously over an -80 km standard single-mode fiber (SMF) transmission based on DFB LD with -1 side mode injection-locked and optoelectronic feedback techniques. For a successful deployment of FTTH/DLOMS transport systems, it is necessary to develop a cost-effective architecture. DFB LD with -1 side mode injection-locked and optoelectronic feedback techniques is a feasible scheme in which injection-locked -1 side mode is used to transmit BB and RF signals. This is an attractive scheme because it avoids the need of expensive and sophisticated dual-parallel modulator with carrier suppression scheme [10]. Thereby, it reveals a prominent one with more economic advantage. Directly modulated BB (1.25 Gbps) and RF (622 Mbps/10 GHz) signals are successfully transmitted simultaneously. Low bit error rate (BER) values and clear eye diagrams were achieved in our proposed FTTH integration with DLOMS transport systems.

2. EXPERIMENTAL SETUP

Figure 1 shows the experimental configuration of our proposed directly modulated FTTH/DLOMS transport systems based on -1 side mode injection-locked and optoelectronic feedback techniques. The solid line represents the optical signal path, and the dash line represents the electrical signal one. The transmitting site is composed of one

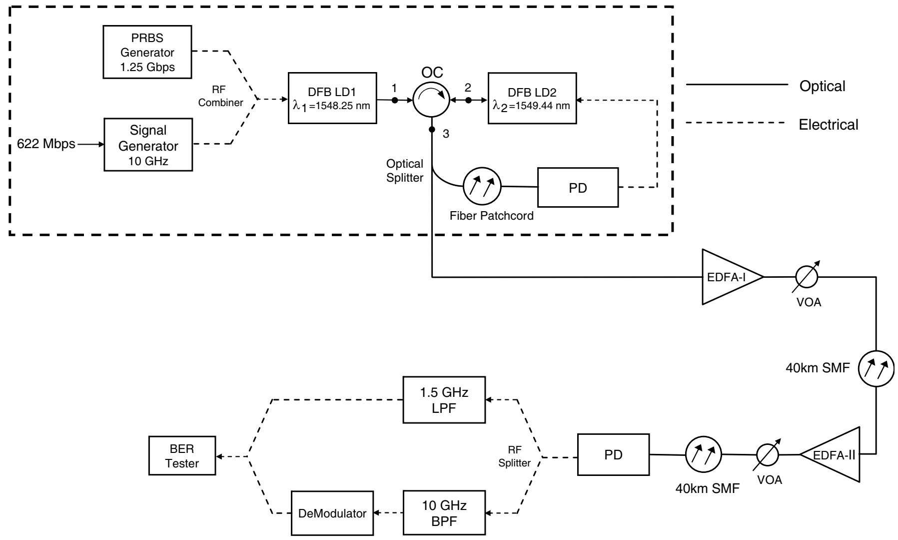

Figure 1. Experimental configuration of our proposed directly modulated FTTH/DLOMS transport systems.

pseudorandom binary sequence (PRBS) generator, one microwave signal generator, two DFB LDs, one optical circulator (OC), and one broadband pin photodiode (PD). The central wavelengths of these two DFB LDs are 1548.25 nm (λ_1) and 1549.44 nm (λ_2), respectively. The 622 Mbps data signal was mixed with a 10 GHz microwave carrier to generate the data stream. A data signal of 1.25 Gbps, with a PRBS length of $2^{15} - 1$, was combined with a RF data stream of 622 Mbps/10 GHz. The combined signals were used to directly modulate the DFB LD1.

The optical output of DFB LD1 was injected into the DFB LD2 via the OC, with an injection power level of -5 dBm. The wavelength of the injected light has been carefully chosen to match with the -1 side mode of slave laser (λ_{-1}) and ensure that the optical enhancement in side mode suppression ratio (SMSR) is achieved. The OC placed between the DFB LD1 and the DFB LD2 prevents the returned laser light to ensure the injection light has totally injected into the DFB LD2. The output of DFB LD1 was coupled into the port 1 of OC, the injection-locked DFB LD2 was coupled into the port 2 of OC1, and the port 3 of OC 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 OC and broadband PD is a fiber patchcord. The broadband PD converts laser light into BB and RF combined signals to directly modulate the DFB LD2. The optical power was amplified by two stages of erbium-doped fiber amplifiers (EDFAs), system link with a transmission length of 80 km consisted of two SMF spans (40 + 40 km). A variable optical attenuator (VOA) was placed at the start of each optical link, thus there would be a reduction in distortions. Over an 80-km SMF transmission, the received optical signal was detected by a broadband PD, separated off by a 1 × 2 RF splitter, and went through 2 separate RF low-pass filter (LPF) and band-pass filters (BPF) (1.5 GHz/LPF and 10 GHz/BPF). The 1.25 Gbps data signal was directly fed into a BER tester for BER analysis, and the 622 Mbps/10 GHz data stream was demodulated and fed into a BER tester for BER analysis.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The resonance frequency f_0 in an injection-locked LD can be expressed as [9]

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

where F_a and F_I are the average photon densities of the mode a and injected light, G_a is the modal gain of mode a; $G_{a,n} = dG_a/dn$, f is the intermodal spacing in the frequency domain; and Γ is the confinement factor. f_0 is enhanced with injection into negative side mode, thereby, the laser resonance frequency under -1 side mode injection-locked is larger than that under main mode injection-locked. And further, the resonance frequency enhancement term $\Delta\omega_R$ can be stated as [10]:

$$\Delta\omega_R = -\frac{\alpha}{2} g[N_0 - N_{th}] + \Delta\omega \tag{2}$$

where g is the gain coefficient; N_0 is the steady-state carrier number; and N_{th} is the threshold carrier number. It is clear from Eq. (2) that the two terms on the right-hand side allow injection-locked laser to significantly enhance the bandwidth. The first term on the right-hand side accounts for the shifting of the slave cavity mode from its free-running frequency by α parameter. As the steady-state carrier number can only be less than the threshold, the first term is positive. The primary enhancement comes from the second term $\Delta\omega$. An optimum locking can be achieved if the frequency of the master laser is lower than the free-running slave laser frequency, i.e., negative detuning. The detuning frequency is defined as $\Delta\omega \equiv \omega_{free} - \omega_{inj}$

(ω_{free} is the frequency of free-running slave laser, ω_{inj} is the frequency of master laser). $\Delta\omega$ is positive as the frequency of free-running slave laser is higher than that of master one. When the LD is modulated by the signal containing frequency components close to the relaxation oscillation frequency, the LD experiences nonlinear coupling between carriers and photons. This nonlinear coupling produces nonlinear distortion, resulting in transmission performance degradation. Nonlinear distortion can be very small as $\Delta\omega_R$ increases largely. The use of -1 side mode injection locking scheme increases the laser resonance frequency, leading to an improvement of transmission performance.

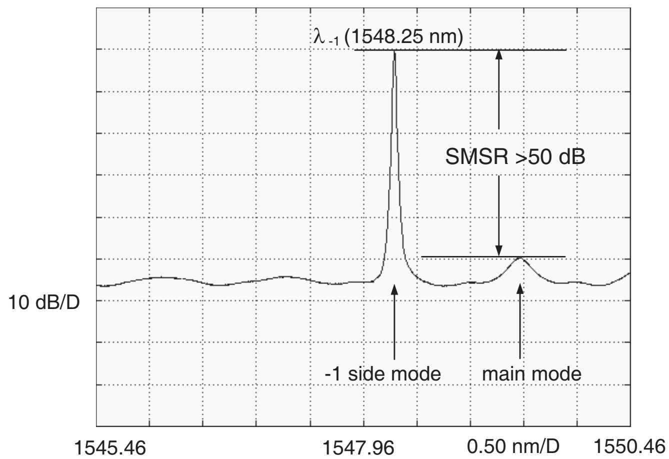

Figure 2. Optical spectrum for -1 side mode injection-locked (λ_{-1}, 1548.25 nm) of DFB LD2.

For -1 side mode injection-locked (λ_{-1}, 1548.25 nm) of DFB LD2, as shown in Figure 2, the SMSR value is larger than 50 dB. The SMSR is found to be [11]:

$$SMSR = \frac{\Gamma v_g g_{noinj}(N) - 1/\tau_p}{\Gamma v_g g_{inj}(N) - 1/\tau_p} \frac{\Gamma\beta_{sp} BN^2 + R_{inj}}{\Gamma\beta_{sp} BN^2} \tag{3}$$

where v_g is the group velocity; $g_{inj}(N)$ and $g_{noinj}(N)$ are the gain for the injected mode and the next strongest mode; τ_p is the photon lifetime; β_{sp} is the spontaneous emission factor, B is the recombination coefficient; N is the carrier density; and R_{inj} is the injection ratio. -1 side mode injection locking is achieved effectively due to the fact that the SMSR value increases. The wavelength of the injected light must be carefully chosen to match the −1 side mode of DFB LD2 and ensure that the optical enhancement in SMSR is achieved.

The rate equations for laser diode with light injection and optoelectronic feedback techniques are given by [12]

$$\frac{\partial n}{\partial t} = \frac{I}{eV} - \frac{n}{\tau_n} - G \cdot P + k_{loop}[P(t-\tau) - P_{av}] \tag{4}$$

$$\frac{\partial P}{\partial t} = \left(G - \frac{1}{\tau_p}\right) P + \frac{2}{\tau_g}\sqrt{PP_i}\cos(\theta) \tag{5}$$

$$\frac{\partial \theta}{\partial t} = -df + \frac{1}{2}\alpha_l(G - G_{si}) - \frac{1}{\tau_g}\sqrt{\frac{P_i}{P}}\sin(\theta) \tag{6}$$

where n is the carrier density; I is the slave pumping current; V is the laser active volume; τ_n is the carrier lifetime; G is the gain; P is the photon density; k_{loop} is the feedback coefficient; τ is the delay of the feedback loop; P_{av} is the average photon density; τ_g is the cavity transit time; P_i is the external injection power; θ is the phase difference between salve and master lasers; df is the frequency detuning; and α_l is the linewidth enhancement factor. The slave laser relaxation oscillation damping rate Γ_f can be derived from the above rate equations. The optoelectronic feedback increases the stability of the laser diode when $\Gamma_f > \Gamma_0$ (damping rate as laser diode only with light injection), resulting in out-of-phase carrier re-injection. The laser resonance frequency f_0 can be stated as

$$f_0^2 = \frac{g_0 P}{4\pi^2 \tau_\rho} \tag{7}$$

where g_0 is the gain coefficient. Out-of-phase carrier re-injection increases the photon density, in which resulting in an improvement of laser resonance frequency.

The second-order harmonic distortion to carrier ratio (HD_2/C) and third-order harmonic distortion to carrier ratio (HD_3/C) of LD are given by [15]:

$$HD_2/C \approx m^2 \cdot |FR(2f_1)|^2 \cdot \left(\frac{f_1}{f_0}\right)^4 \tag{8}$$

$$HD_3/C \approx m^4 \cdot \left[\left\{\left(\frac{f_1}{f_0}\right)^4 - \frac{f_1^2}{2f_0^2}\right\}^2 + \left(\frac{f_1}{f_0}\right)^2 \left\{\frac{1}{4\pi f_0 \tau_n} - \left(\frac{f_1}{f_0}\right)^2 \left(2\pi f_0 \tau_p + \frac{3}{4\pi f_0 \tau_n} + \frac{3\varepsilon S_0}{2\pi f_0 \tau_p}\right)\right\}^2\right] \tag{9}$$

where m is the optical modulation index; $FR(f_1)$ is the small-signal frequency response; f_1 is the modulation frequency; S_0 is the photon density; and ε is the gain compression parameter with respect to photon density. Both HD_2/C and HD_3/C values are decreased as f_0 is increased. The use of -1 side mode injection-locked and optoelectronic feedback techniques enhance laser resonance frequency, causing system with lower HD_2/C and HD_3/C, finally leading to an improvement of transmission performance.

The measured and simulated BER curves for FTTH and DLOMS applications as a function of the received optical power level for free running, with -5 dBm -1 side mode injection, as well as with -5 dBm -1 side mode injection and optoelectronic feedback are plotted in Figures 3(a) and (b), respectively. Free-running here refers to that the DFB LD1 is transmitted directly without the use of DFB LD2. The combined BB and RF signals are employed to modulate the DFB LD1 directly. As to measured results for 1.25 Gbps data signal at a BER of 10^{-9}, in the free-running case, the received optical power level is -26 dBm; with -5 dBm -1 side mode injection, the received optical power level is -31.9 dBm; with -5 dBm -1 side mode injection and optoelectronic feedback, the received optical power is -34.2 dBm. There is a power penalty of $\sim$8 dB for the free-running case when compared to the -1 side mode injection and optoelectronic feedback. As to measured results for 622 Mbps/10 GHz data stream at a BER of 10^{-9}, in the free-running case, the received optical power level is -27.4 dBm; with -5 dBm -1 side mode injection, the received optical power level is -33.4 dBm; with -5 dBm -1 side mode injection and optoelectronic feedback, the received optical power level is -35.8 dBm. Compared to the free-running case, 8.4 dB of the received optical power reduction is achieved as light injection and optoelectronic feedback techniques are simultaneously to reduce the degradation factor of signal fading because of fiber dispersion. Signal fading occurs due to the interaction between the propagating signal in the fiber and the dispersion. The use of -1 side mode injection and optoelectronic feedback techniques not only reduces the dispersion in the transmission fiber but also overcomes system limitations imposed by optical double sideband generation at the optical transmitter, leading to BER performance improvement. From Figures 3(a) and (b), it can also be seen that the simulated results match the measured (experimental) results, i.e., these simulated results confirm the accuracy of the experimental results.

Most injection-locking experiments involving data transmission have the slave laser (DFB LD2) modulated. In this experiment, however, the master laser (DFB LD1) is modulated. It has been

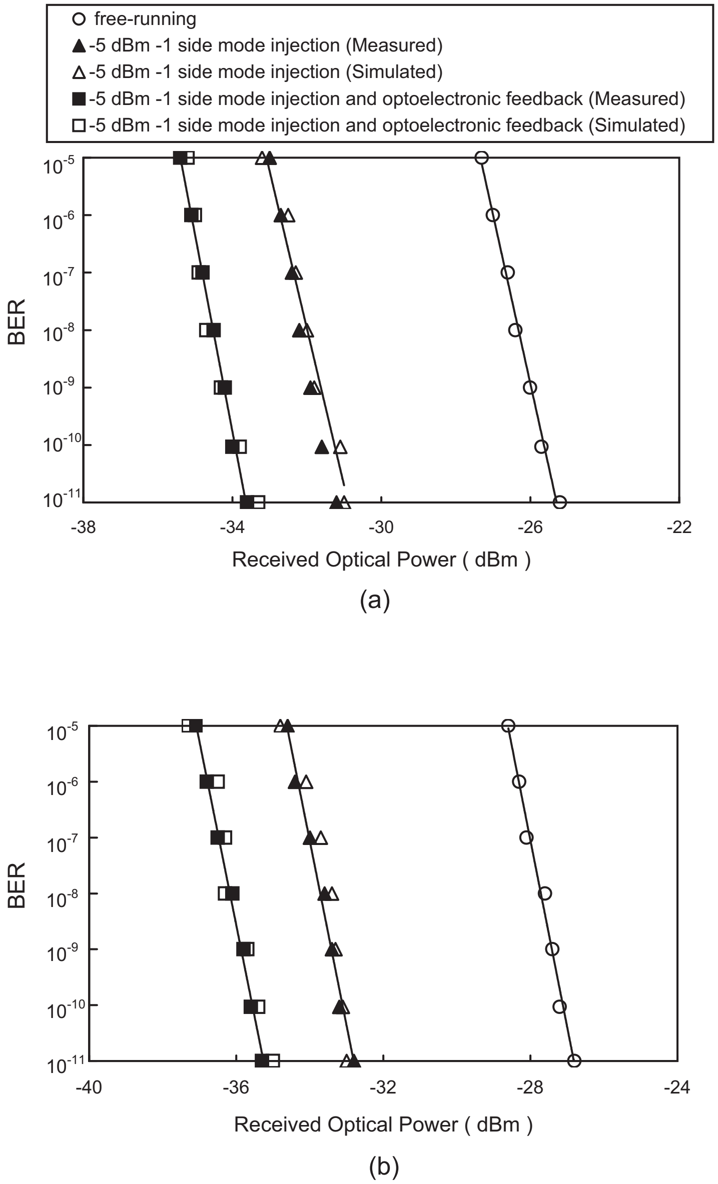

Figure 3. (a) Measured and simulated BER curves for FTTH application as a function of the received optical power level. (b) Measured and simulated BER curves for DLOMS application as a function of the received optical power level.

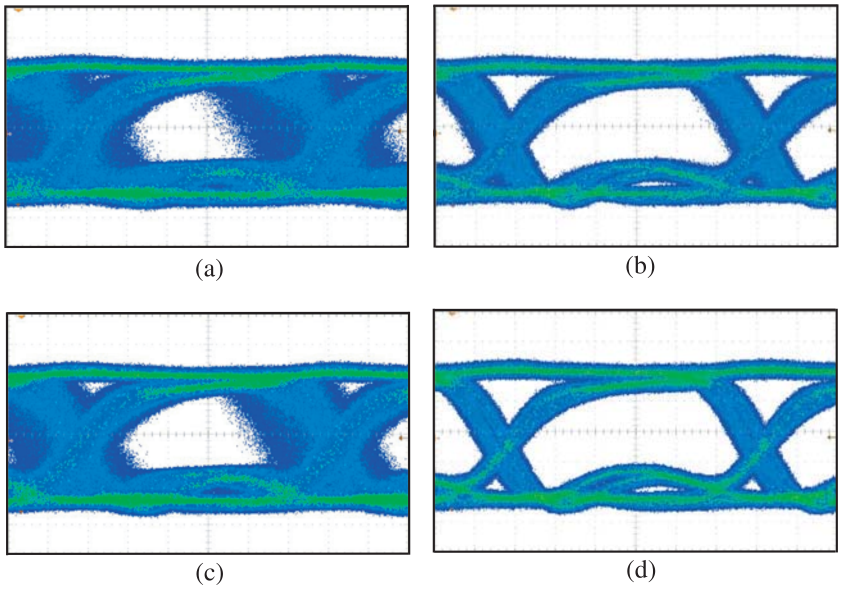

Figure 4. (a) Eye diagram of 1.25 Gbps data signal for free-running. (b) Eye diagram of 1.25 Gbps data signal with −1 side mode injection and optoelectronic feedback. (c) Eye diagram of 622 Mbps/10 GHz data stream for free-running. (d) Eye diagram of 622 Mbps/10 GHz data stream with −1 side mode injection and optoelectronic feedback.

previously predicted that in such a configuration, there should be a significant attenuation of the data [13]. In this experiment, with −1 side mode injection only, the modulation suppression is 28 dB. However, with simultaneous −1 side mode injection and optoelectronic feedback techniques, the modulation suppression is decreased to 10 dB, i.e., systems' transmission performance affected by low modulation suppression value is limited. −1 side mode injection and optoelectronic feedback techniques cause carrier re-injection, thereby increase the laser resonance frequency and lead to the reduction of threshold current, as well as result in higher optical power launched into the fiber. The higher optical power we get, the lower modulation suppression we obtain. −1 side mode injection and optoelectronic feedback techniques are used as compensation schemes to compensate for the modulation suppression. If DFB LD1 is used alone to transmit signals over fiber link, then the modulation suppression can be avoided. It seems to be more advantageous to simply transmit DFB LD1 directly. However, it is worth using −1 side mode injection and optoelectronic feedback techniques because the performances of slave laser (DFB LD2) can be improved with not only enhanced bandwidth and SMSR value, but also lower threshold current and frequency chirp. All of these will lead to superior transmission performance. Our proposal reveals a prominent one compared with that of systems with single DFB LD.

Figures 4(a) and (b) display the eye diagrams of 1.25 Gbps data signal for free-running and with −1 side mode injection and optoelectronic feedback, respectively, over an 80-km SMF transmission. Figures 4(c) and (d) display the eye diagrams of 622 Mbps/10 GHz data stream for free-running and with −1 side mode injection and optoelectronic feedback, respectively, over an 80-km SMF transmission. Amplitude and jitter fluctuations in the signals are clearly observed in both free-running cases (Figures 4(a) and (c)) due to fiber dispersion. Signal distortion will give an increase in power penalty. However, in both −1 side mode injection and optoelectronic feedback cases (Figures 4(b) and (d)), amplitude and jitter fluctuations in the signals are clearly reduced.

4. CONCLUSION

We proposed and demonstrated a directly modulated FTTH/DLOMS transport system based on −1 side mode injection-locked and optoelectronic feedback techniques. Simultaneous transmission of BB and RF signals in a directly modulated form, low BER values and clear eye diagrams were achieved in our proposed systems. Such a proposed FTTH/DLOMS transport system will benefit the deployment of the broadband access networks.

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