The Optical Injection Locking Technique Applied to the Filtering and Remodulation of WDM Channels

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***Abstract* — The use of the optical injection locking technique for information processing in WDM systems is experimentally investigated. As the locking bandwidth is controlled by the amount of injected optical power, only the WDM carrier within a given locking range induces the locking of the slave semiconductor laser and is properly transmitted. The other carriers are absorbed inside the laser structure. In addition, by using a feed-forward laser current approach along with the injection process, the remodulation and/or reshaping of the selected channel information can be performed. It was experimentally observed that injection-locked feed-forwarded semiconductor lasers have the potential to be used as optical filters, offering up to 40 dB extinction ratio, and as remodulators, for a 940 Mb/s optical channel.**

***Index Terms* — semiconductor lasers, optical injection locking, optical filters, WDM systems.**

I. Introduction

Recently, due to the increasing demand for high capacity systems, multiplexing techniques [1] have been applied to different physical transmission mediums [2]. One approach that became successful after the development of the Erbium doped fiber amplifiers (EDFA) uses the optical fiber and the wavelength division multiplexing (WDM). In optical WDM systems, several channels allocated at different optical wavelengths are combined and simultaneously transmitted by an optical fiber. The system can support high bit rates and offer, at same time, security and reliability. At the receiver end, the channels are separated. Samples of the combined optical signal are individually filtered by optical filters centered at the different channel carrier frequencies (or wavelengths). Unfortunately, the wide bandwidth of these filters is one of the causes for the restriction on the maximum number of transmission channels in WDM systems [1] that can be amplified by the EDFAs.

Under optical injection locking (OIL), a laser, called slave laser (SL), operates at the same frequency as that of another laser, called master laser (ML). During the locking condition, the SL gain dynamics are altered, inducing the SL noise characteristics to be the same as those of the ML. The two lasers remain locked while the frequency difference between them is within the OIL range. Normally, the locking range is narrow (< 10 GHz) and controlled by the amount of injected optical power. If the WDM optical carriers were simultaneously coupled into a SL, only the channel whose frequency is close enough to that of the SL (inside the locking range) would induce the SL to operate at same channel frequency. In this way, the SL would reproduce the ML signal characteristics with high output power, while attenuating the other channels by optical absorption. As a result, the OIL could be used in the optical filtering of WDM channels with the advantage of allowing closer channel spacing due to the narrow locking range.

A closer investigation of the OIL process revels that, inside the locking range, the SL output optical power can suffer an almost linear variation, depending on the instantaneous free-running (no injection) frequency difference between the ML and SL. Normally, if DFB semiconductor lasers are used, the optical power reaches a maximum for negative frequency detuning (ML frequency > SL frequency) and a minimum for positive detuning. Therefore, if the free-running frequency difference can be adequately controlled, it is possible to alter the level of the SL output optical power accordingly. As in semiconductor lasers the optical frequency is varied by the electronic bias current, it would be possible to tune the SL free-running frequency to properly amplitude modulate the locked laser. In this way, the OIL process could also be employed in the remodulation of the filtered WDM channel, as the incoming signal is substituted by the processed SL signal.

In this paper, the use of the optical injection locking technique in WDM receivers for information processing is experimentally investigated. First, theoretical concepts of the optical injection locking process are discussed. Following, the block diagram for the OIL filtering experimental set-up is presented. Modifications were implemented in this set-up to allow the remodulation /reshaping experiment to be performed using the injection locking technique and a feed-forward approach. Finally, the experimental results are presented and analyzed.

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II. THEORY

Fig. 1 shows the a simplified block diagram of an OIL experiment [3]. The ML light is injected into the SL active region, after an isolator. The isolator prevents SL coupling into the ML. If the ML and SL optical frequencies are sufficiently close so that the frequency difference is within the locking range, the gain mechanisms of the SL are altered to force its optical frequency to be the same as that of the ML. The lasers are kept locked while the free-running frequency difference between ML and SL is inside a so called locking range. As mentioned before, under OIL, both lasers operate at the same frequency, with the SL following all phase fluctuations of the ML.

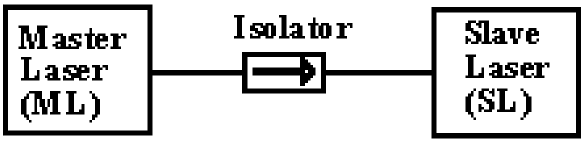


Fig. 1. Block diagram for the OIL system

The interaction of the electric field with the leasing medium can be evaluated by a set of coupled differential rate equations. Assuming that the lasers are single mode and the system is locked, the SL rate equations can be expressed by [4-5]:

$$\frac{dE_s(t)}{dt} = \left\{ j\omega_s + \frac{1}{2}\left[G(t) - \frac{1}{\tau_p} \right] \right\} E_s(t) + \frac{\sqrt{\eta}}{\tau_i} E_m(t) \quad (1)$$

$$\frac{dn_c(t)}{dt} = D\left(\nabla^2 n_c\right) + \frac{J}{ed} - \frac{n_c}{\tau_s} - \mathrm{Re}[G(t)] n_{photon} \quad (2)$$

where ω_s is the free-running slave laser angular frequency (rad/s), $G(t)$ is the complex gain (s^{-1}), τ_p is the photon life time (s), η is a term representing the coupling efficiency of the master laser injected signal, τ_i is the round trip time (s), $n_C(t)$ is the carrier density (m^{-3}), D is the diffusion coefficient (m^2s^{-1}), τ_s is the carrier lifetime, n_{photon} is the photon density, J represents the carrier injection term (Am^{-2}), e is the electron charge (C) and d is the active layer thickness (m). In (1), under OIL, the ML and SL complex electric fields can be respectively expressed as:

$$E_m(t) = E_{mo}(t) e^{j[\omega_m t + \phi_m(t)]} \quad (3a)$$

$$E_s(t) = E_{so}(t) e^{j[\omega_m t + \phi_S(t)]} \quad (3b)$$

where E_{so} and E_{mo}, and $\phi_s(t)$ and $\phi_m(t)$, are, respectively, the SL and ML electric field amplitudes and phases (rad). The ML angular frequency is ω_m (rad/s). By recalling that the electric field amplitude is proportional to the square root of the photon number, (1) can be divided into two equations [4-5]:

$$\frac{dI_s(t)}{dt} = \left[\mathrm{Re}[G(t)] - \frac{1}{\tau_p} \right] I_s(t) + \frac{2\sqrt{\eta I_s(t) I_m(t)}}{\tau_i} \cos\theta(t) + R \quad (4)$$

$$\frac{d\phi_s(t)}{dt} = \omega_s - \omega_m + \frac{1}{2}\mathrm{Im}[G(t)] + \frac{1}{\tau_i}\sqrt{\frac{\eta I_m(t)}{I_m(t)}} sin\theta(t) \quad (5)$$

where $I_s(t)$ and $I_m(t)$ are, respectively, the SL and ML photons numbers. In both (4) and (5), $\theta(t) = \phi_m(t) - \phi_s(t)$.

By assuming that the carrier diffusion inside the SL structure is negligible, (2) can be rewritten in terms of the carrier number N [4-5]:

$$\frac{dN(t)}{dt} = \frac{i(t)}{e} - \frac{N(t)}{\tau_s} - \mathrm{Re}[G(t)] I_s(t) \quad (6)$$

where $i(t)$ is the SL current (A). In order to simplify the coupled non-homogenous differential equations (4) to (6), the time-dependent terms can be linearized and solved using the approximation of small perturbations around the steady state values. Thus, a variable $A(t)$ can be expressed as $A(t) = A_o + \hat{a}(t)$, where A_o represents the $A(t)$ stationary value and $\hat{a}(t)$ (where $\hat{a}(t) << A_o$) is the perturbation around the stationary value A_o. The complex SL gain $G(t)$, within a first order approximation, can be written as [4]:

$$G(t) = G_o + G_I \hat{i}_s(t) + G_N(1 + j\alpha)[\Delta N_o + \hat{n}(t)] \quad (7)$$

where $\Delta N_o = N_o - \tilde{N}_o$, N_o is the SL carrier number under injection, $\tilde{N}_o$ represents the free-running steady state carrier number, G_o is the free-running gain per unit of time (s^{-1}), $G_N = \delta G/\delta N$ is differential gain related to the carrier number (s^{-1}), $G_I = \delta G/\delta I$ is differential gain (s^{-1}) related to the photon number, and α is the linewidth enhancement factor and accounts for the phase-amplitude coupling of the electric field. The $\hat{i}_s(t)$ and $\hat{n}(t)$ terms represent the oscillations (perturbations) around the stationary values for photon number and carrier number, respectively.

For the purposes of this paper, the stationary solutions of the linearized differential equations are sufficient. Thus, after a proper mathematical manipulation, the stationary solutions for the OIL process are given by :

$$\Delta G = G_N \Delta N_o = -\frac{v_g}{L}\sqrt{\frac{\eta I_{mo}}{I_{so}}} \cos\theta_o \quad (8)$$

$$\Delta\omega = \omega_m - \omega_s = -\frac{v_g}{2L}\sqrt{\frac{\eta I_{mo}}{I_{so}}}\left(sin\theta_o - \alpha\cos\theta_o \right) \quad (9)$$

$$I_{so} = \frac{G_o \tilde{I}_{so} - \dfrac{\Delta N_o}{\tau_s}}{G_o + \Delta G} \qquad (10)$$

where I_{so} is the SL steady state photon number under injection, I_{mo} is the ML steady state photon number, $\tilde{I}_{so}$ is the free-running SL steady state photon number, v_g is the group velocity (m/s), L is the SL effective cavity length (m), and θ_o is the steady state phase difference between ML and SL (rad).

Equation (9) is of particular interest for the injection locking process. It defines the injection locking bandwidth of the OIL system [6]. It is possible to observe that the width of the locking range is related to the amount of injected optical power. Therefore, for a given injection level, locking can only be achieved if the free-running frequency difference between the ML and SL falls within this range. Therefore, in WDM systems, any injected optical channel whose frequency lays outside the locking bandwidth would cause no changes in the dynamics of the SL, being mainly attenuated by absorption. On the other hand, only the channel wavelength that causes laser locking would be properly photodetected.

As it can be seen in (8) and (10), the SL gain (ΔG) and photon number (I_{so}) are also susceptible to changes due to oscillations in the injected ML photon number. Hence, it is possible that the SL output signal presents the same oscillating nature as that of the ML signal. By recalling that the electronic SL bias current can also alter the photon number (through G_o), a proper combination of effects would allow to maximize or minimize the oscillation contents of the SL signal. If the oscillations in the ML signal correspond to intensity modulation, the SL laser could perform the remodulation, reshaping, and/or erasing of the information for a given WDM channel.

III. Experimental Results

Fig. 2 shows the block diagram for the OIL filtering experimental set-up. The signals from two semiconductor lasers, ML1 and ML2, are amplified and simultaneously coupled into active region of the SL, after two 3dB fiber couplers. In a single facet arrangement, the light emitted by SL is coupled into an optical spectrum analyzer. Isolators prevent the SL light and retro-reflections to be coupled into the ML1 and ML2. Polarization controllers are used to improve the polarization matching of different wavefronts. By assuming that the SL is selected to filter out the ML2 signal, the coupling of the two ML signals results in the locking of the SL in relation to ML1. Thus, the ML2 photons have practically no influence in the SL gain mechanism changes and, as a result, the stimulated emissions in this frequency are rather small. As a result, the photons at the ML2 frequency tend to spread or be absorbed inside the SL active region. Consequently, only a small number of ML2 photons are able to leave the SL cavity and be detected.

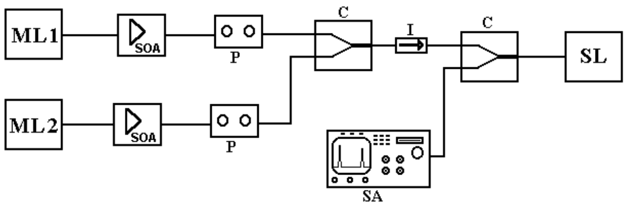


Fig. 2. Block diagram for optical filtering experiment using the OIL process. SOA: semiconductor optical amplifier; P: polarization controller; I: isolator; C: fiber coupler; SA: optical spectrum analyzer.

Fig. 3 shows the experimental block diagram for the investigation of the remodulation, reshaping and erasing properties of the OIL. In this experiment, the ML signal is externally modulated, amplified by a semiconductor optical amplifier (SOA) and divided into two different optical paths. One part of the ML signal is injected into the SL (path 1). The other is photodetected (path 2). The AC photocurrent is amplified and combined with the SL bias current. The process described for path 2 is responsible for the SL current control. In other words, a sample of the modulated ML optical signal is feed-forward into the SL via the bias current. If the two path lengths are closely matched, the modulated ML signal is electronically and optically coupled into the SL and, as previously described, the oscillations caused by the intensity modulation produce simultaneous gain and photon number variations. Therefore, by using an adequate phase combination for the optical and electronic signals, it is possible to obtain remodulation and/or reshaping of the optical carrier information. An optical oscilloscope was used to analyze the signals before and after the SL.

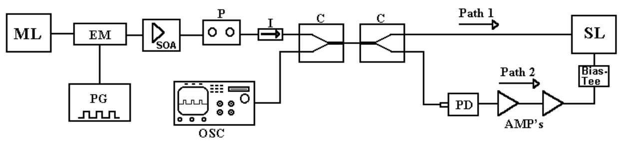
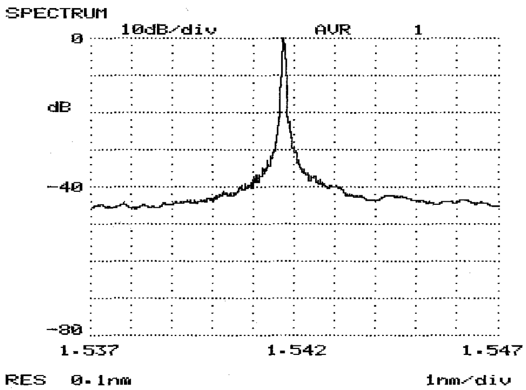


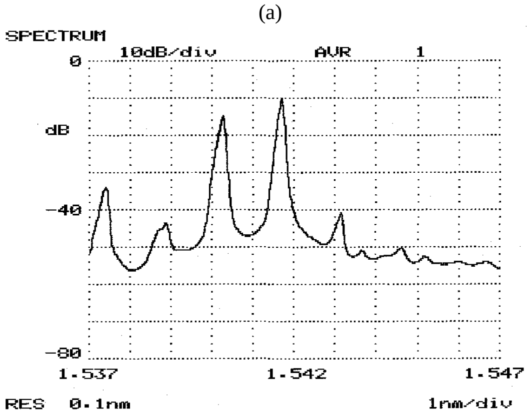
Fig. 3. Block diagram for the OIL remodulation experiment. PG: pulse generator; EM: external modulator; SOA: semiconductor optical amplifier; P: polarization controller; I: isolator; C: fiber coupler; PD: photodetector; OSC: optical signal analyzer (oscilloscope).

To investigate the injection locking effect, the set-up shown in Fig. 2 was adapted for the measurement of the optical spectra of the ML, the SL, and the locked SL. The results are presented in Fig. 4. The master laser (ML1) was a tunable 1550 nm external cavity semiconductor laser (Photonetics) operating at 60 mA. The ML was tuned by mechanical (rough) and thermal (precise) adjustments to match one of the SL mode wavelengths. The SL was a base-mounted Fabry-Perot (FP) semiconductor laser, operating at 60 mA. By referring back to Fig. 2, at the SL end, it was necessary to use bulk optics to allow access to the only available SL facet. Hence, the ML1 signal was collimated after the second optical fiber coupler and coupled into the SL cavity. Reflections and the SL emission followed the same optical path, but in the opposite direction. To measure Fig. 4(a), the optical spectrum analyzer was connected after the isolator in Fig. 2. The measurements of Fig. 4(b) and (c) were obtained as in the original set-up. The ML1, whose spectrum is presented in Fig. 4(a), was tuned to closely match one of the SL mode wavelengths, Fig. 4(b). By controlling the SL temperature, locking happened at 1541.75 nm, as shown in Fig. 4(c). It can be seen that the SL multimode characteristics of Fig. 4(b) disappear once the SL operates in the locked mode. As expected from the injection locking process, the SL phase noise content is suppressed and its spectrum becomes similar to that of the master laser, as in Fig. 4(a) and (c).

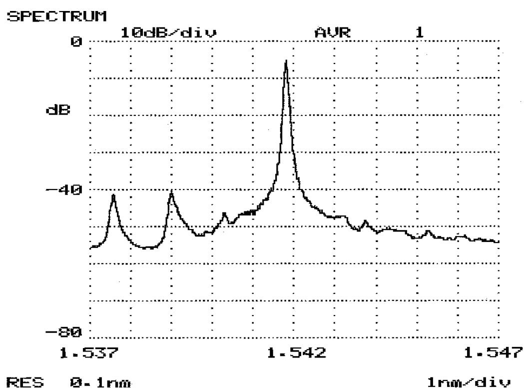
In the OIL filtering experiment, ML1 and SL are the same as above. The ML2 was a non-tunable external cavity semiconductor laser (E-Tek Ind.) operating at 1548.95 nm and 120 mA bias current. Both ML1 and ML2 presented low intensity and phase noises. The first coupler in Fig. 2 is responsible by the combination of the ML1 and ML2 signals. Fig 5(a) shows the ML1 and ML2 optical spectra, measured after isolator output. It is possible to observe that the difference between the ML1 and ML2 power levels is around 4 dB. Fig. 5(b) shows the measured spectra when the spectrum analyzer is used as in Fig. 2. The OIL filtering process increases the power level difference to around 14 dB. Nevertheless, due to the discrete components used in the experiment, a strong optical reflection in the fiber-air interface was observed



(a)

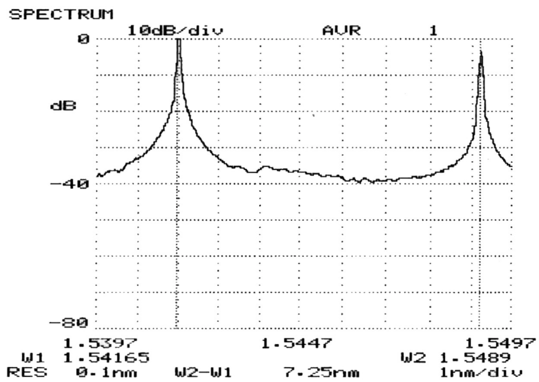


(b)

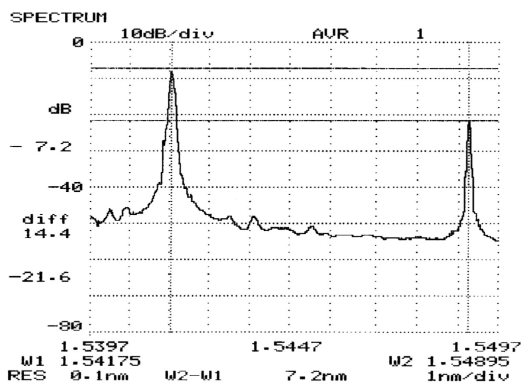


(c)

Fig. 4. Optical spectrum of the master laser (a), slave laser (b), and locked slave laser (c).



(a)

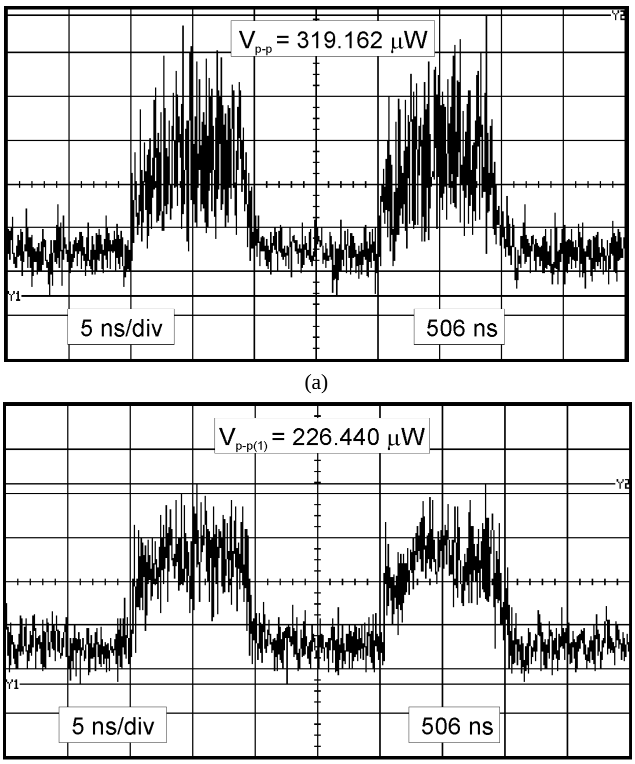


(b)

Fig. 5. Optical filtering using the OIL process, (a) with no injection and (b) with injection.

after the second coupler. Additional measurements verified that the ML2 power level could drop further 25 dB if the reflection effect were eliminated.

To perform the experiment represented by Fig. 3, the set-up was modified and LM2 was removed. All operational characteristics of the ML1 and SL were kept the same. An external modulator (Sumitomo Inc.) modulated the ML1 signal at 940 Mb/s, using a HP 8131A signal generator. A 300kHz-6GHz photodetector (HP 83411A) was used to detect a sample of the ML1 optical signal. The AC current coupled into the SL was 3 mA_{RMS}. The SL bias current was 60 mA. Fig. 6 shows the plots obtained from an optical oscilloscope (HP 83480), where the effect of the OIL over the direct modulation of the SL current by the electronic ML sampled signal is observed. It is possible to verify that, under locking, Fig. 6(b), the modulated SL signal becomes less noisy than the signal with no injection, Fig. 6(a). The reason for this behavior comes from the fact that the SL, under OIL, acquires the ML noise characteristics. As the ML is an external cavity laser, its low phase noise contents are passed to the noisy FP laser when locking is achieved.

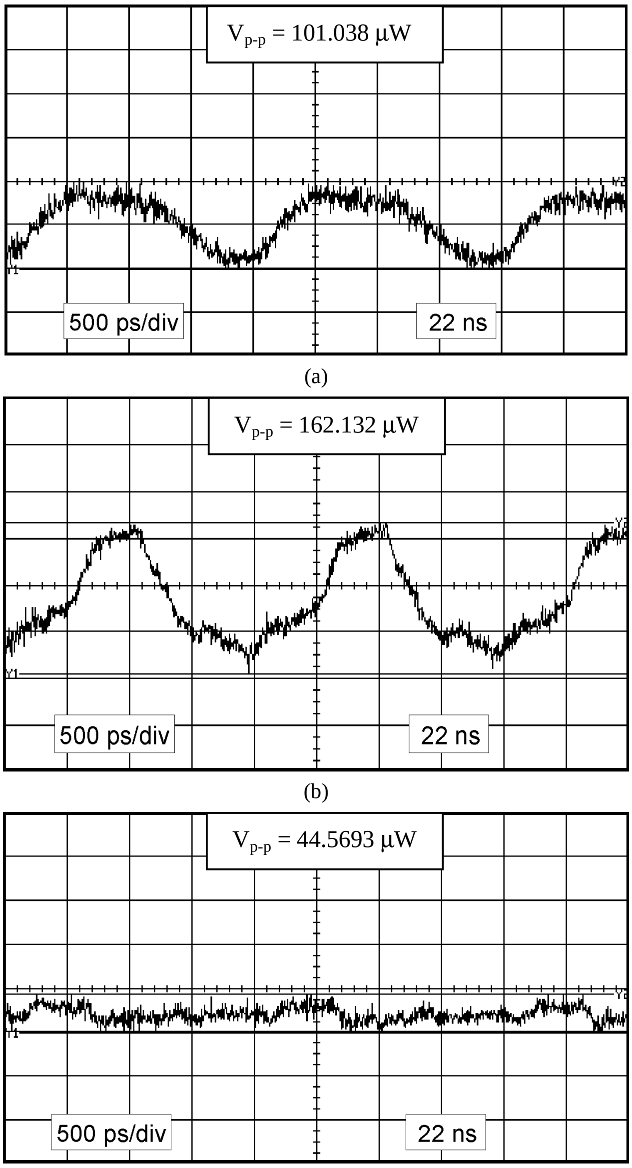


(a)

(b)

Fig. 6. The SL output siganl (a) without locking and (b) under locking.

Fig. 7 shows the results for the information processing experiment. Fig 6(a) shows the photodetected SL signal when no locking is present and the SL is modulated by the feed-forward current. Once that SL is locked, the adjustment of the phase between the optical and electronic injection signals can generate two distinct effects. In the first one, both signals (electronic and optical) are in phase, Fig. 6(b), causing the peak-to-peak value of the SL modulated signal monitored by the oscilloscope to increase from 101 uW, Fig 6(a), to 162 uW. Although the remodulated pulse shape is different from that of the pulse without injection, the central region of the pulse in Fig. 6(b) allows a clear distinction between logic levels so that clock recovery would be possible. Fig 6(c) presents the second effect, when the signals are near to a 180-degree detuning. It is possible to observe that the differences between the maximum and minimum levels decrease considerably. By observing the peak-to-peak value in Fig. 6(c), it is almost impossible to distinguish between logic



(a)

(b)

(c)

Fig. 7. The SL output signal with feed-forward: (a) without locking, (b) under remodulation, and (c) under erasing.

levels. This response, called information erasing, would presumably induce logical receivers to interpret the data stream as composed only by low logic levels.

It is believed that these results can be optimized if a better quality SL is used in the experiment. The available SL had a low quantum efficiency and a poor direct modulation response. Also, its complex structure made optical coupling difficult, so that ML signal amplification was necessary. The adjustment of the phase difference between optical and electronic signals was also difficult. The phase control was obtained from fine tuning of the operation frequency (470 MHz or 940 Mbps) at the pulse generator. As a result, the signal remodulation was poor. Despite the problems, it was possible to demonstrate the feasibility of the process.

IV. Conclusions

In this paper, the utilization of the optical injection locking technique for filtering and remodulation/reshaping of optical channels was experimentally investigated. It was observed that the OIL filtering has the potential to suppress undesirable optical carriers by up to 40 dB. Also, it was demonstrated that the OIL can be used in the remodulation (amplification and erasing) of the information in optical carriers. In the amplification process, the signal level was almost doubled. In the erasing application, it dropped to less than 40 % of the original value. In spite of the deficiencies observed in the experimental set-up, the results were within the expected. A theory review is necessary to compensate for the linearization adopted in Section II, which is only valid within certain limits. It is expected that a more detailed analysis of OIL process could help in the development of more sophisticated electronic projects to improve the SL signal coupling.

References

[1] R. Ramaswami e K. N. Sivarajan, “Optical Networks – A Practical Perspective”, first edition, Morgan Kaufmann Publishers, San Francisco, USA, 1998.

[2] R. Ohmoto, H. Ohtsuka e H. Ichikawa, “Fiber-optic microcell radio systems with spectrum delivery scheme”, *IEEE Trans. Vehic. Technol.*, vol. 11, no. 7, pp. 1108-1117, 1993.

[3] A. C. Bordonalli, C. Walton e A. J. Seeds, “High-performance phase locking of wide linewidth semiconductor lasers by combined use of optical injection locking and optical phase-lock loop”, *IEEE J. Lightwave Technol.*, vol. 12, no. 2, pp. 328-342, 1999.

[4] O. Lidoyne, P. Gallion, C. Chabran e G. Debarge, “ Locking range, phase noise and power spectrum of an injection locked semiconductor laser”, *IEE Proc*., vol. 137, pt. J, no. 3, pp. 147-154, 1990.

[5] G. P. Agrawal e N. K. Dutta, "Semiconductor Lasers", second edition, Van Nostrand Reinhold, New York, USA, 1993.

[6] I. Petitbon, P. Gallion, G. Debarge e C. Chabran, “ Locking bandwidth and relaxation oscillation of an injection locked semiconductor laser”, *IEEE J. Quantum Electron*., vol. 24, no. 2, pp. 148-154, 1988.