Chirp reduction and on/off contrast enhancement via optical injection locking and coherent carrier manipulation

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ABSTRACT

The most cost-effective solution for modulating data on an optical carrier is via direct modulation of a semiconductor laser. Unfortunately, this technique suffers from high chirp. Although the chirp can be reduced by reducing the on/off modulation contrast ratio, keeping the signaling laser well above its threshold when transmitting both, logical '0' and '1', this results in limited on/off modulation contrast. There are several techniques for further suppression of the chirp, generally based on self-injection or optical injection locking of the directly-modulated laser (slave) to another laser (master) that emits cw light. However, this technique is very efficient only when the slave laser is operated well above the threshold, almost entirely removing the chirp, but not addressing the issue of limited on/off modulation contrast.

Keywords: Optical communications, Optical injection locking

1. INTRODUCTION

Metro and access networks are very cost sensitive, as the hardware used is shared by a small group of users. Thus, direct modulation of the signaling laser is by far the most preferred approach, which does not require any additional optical hardware and uses only modest amount of RF power[1] for the electro-optic conversion. Unfortunately, direct modulation produces a large chirp (as – besides changing the amplitude - the laser carrier frequency is changed significantly during the modulation of the laser bias current). This chirp causes spectral broadening of the modulated signal, which in turns significantly lowers the signal resilience to chromatic dispersion and thus also limits the reach and modulation speed. As a result, today's commercially-available direct modulation lasers are generally used up to speeds of 2.5 Gbit/s. By a special design, this number can be increased to 10 Gbit/s with reach of 200 km[1]. One of the approaches/contributions towards reduction of the chirp is to scarify the modulation depth. This is because the chirp is the most severe when operating the laser close to its threshold. Thus, operating it all the time well above threshold reduces the chirp, but on the expense of the modulation depth. As a consequence, the modulation depth is generally 3-7 dB.

One of alternative methods that significantly suppresses the chirp is optical injection locking[2]. The schematics is shown in Figure 1 – a continuous-wave (CW) laser ('Master') is injected into a cavity of a directly-modulated semiconductor laser ('Slave'). Provided the emission wavelength of the free running master and slave are close enough, the slave gets frequency locked to the master and emits at the same frequency, even when being amplitude-modulated via direct bias current modulation.

Here, we propose to modify the optical injection locking scheme to suppress not only the chirp, but also to improve the modulation contrast. The proposed scheme takes advantage of the fact that the modulated slave and the master are mutually coherent. Subsequently, by a destructive interference between a portion of the light emitted by the CW master and that of the modulated slave, the intensity of the logical '0' can be bring to zero intensity, although the slave is operated all the time well above the threshold.

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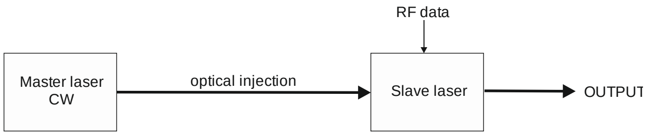


Figure 1. Schematics of optical injection.

2. PRINCIPLE OF OPERATION

Before explaining the concept in detail, let us first introduce constellation representation of the signals we are going to deal with. Constellation represents complex electrical field in the complex plain, Figure 2. We can either characterize the field by the amplitude and phase or by Cartesian co-ordinates in terms of real and imaginary part of the electrical field vector. The real part is commonly called 'In-phase', I, component, while the imaginary one 'Quadrature', Q, component.

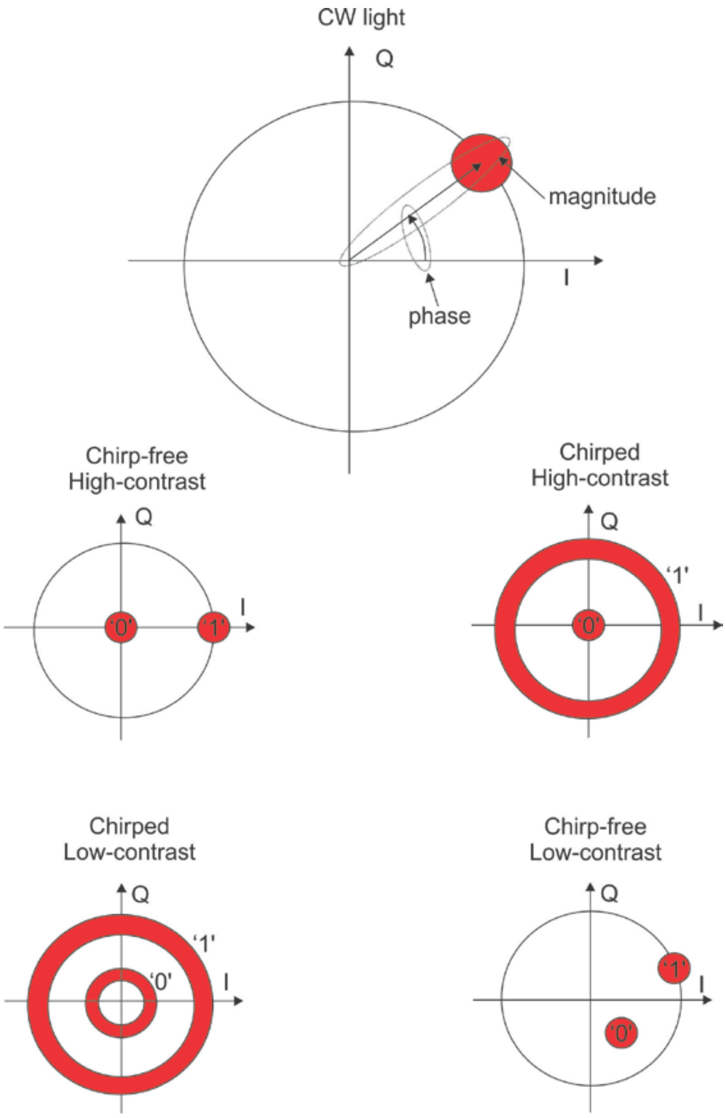


Figure 2. Constellation representation of optical filed (I: In phase, Q: Quadrature component of the electric field intensity) for signals that are chirped or chirp free and/or are of high modulation contrast or low modulation contrast.

The chirp-free, high contrast on-off-keyed signal can be then represented by two points representing the two logical values, Figure 2 – one of them being at zero (optical filed is zero, logical ‘0’) and the other one having finite intensity, and a constant phase (0 deg shown in Figure 2). As described earlier, directly-modulated laser suffers from high chirp, which can be represented in constellation, Figure 2 as a ring for logical ‘1’ – simply, the magnitude is constant, but the phase could have any value. The situation is even worse when considering low modulation contrast signal, Figure 2, in which logical ‘0’ is also characterized by a ring (the phase can have any value), but it has smaller diameter, as logical ‘0’ has lower intensity than logical ‘1’. The last possible case is a chirp-free signal with limited contrast, Figure 2, in which both ‘0’ and ‘1’ are represented by points (both have constant phases and amplitudes) rather than rings, logical ‘1’ has larger magnitude than ‘0’, but generally does not have the same phase.

Now, we can explain how our technique works, Figure 3. First, by injection locking of a low-modulation contrast directly-modulated laser we reduce the chirp, obtaining low-contrast chirp-free signal. Following this step, we interfere the modulated signal with a portion of the master CW signal to achieve fully destructive interference between the logical ‘0’ and the CW. This produces zero magnitude of the ‘0’ logical level, resulting in high contrast ratio, Figure 3.

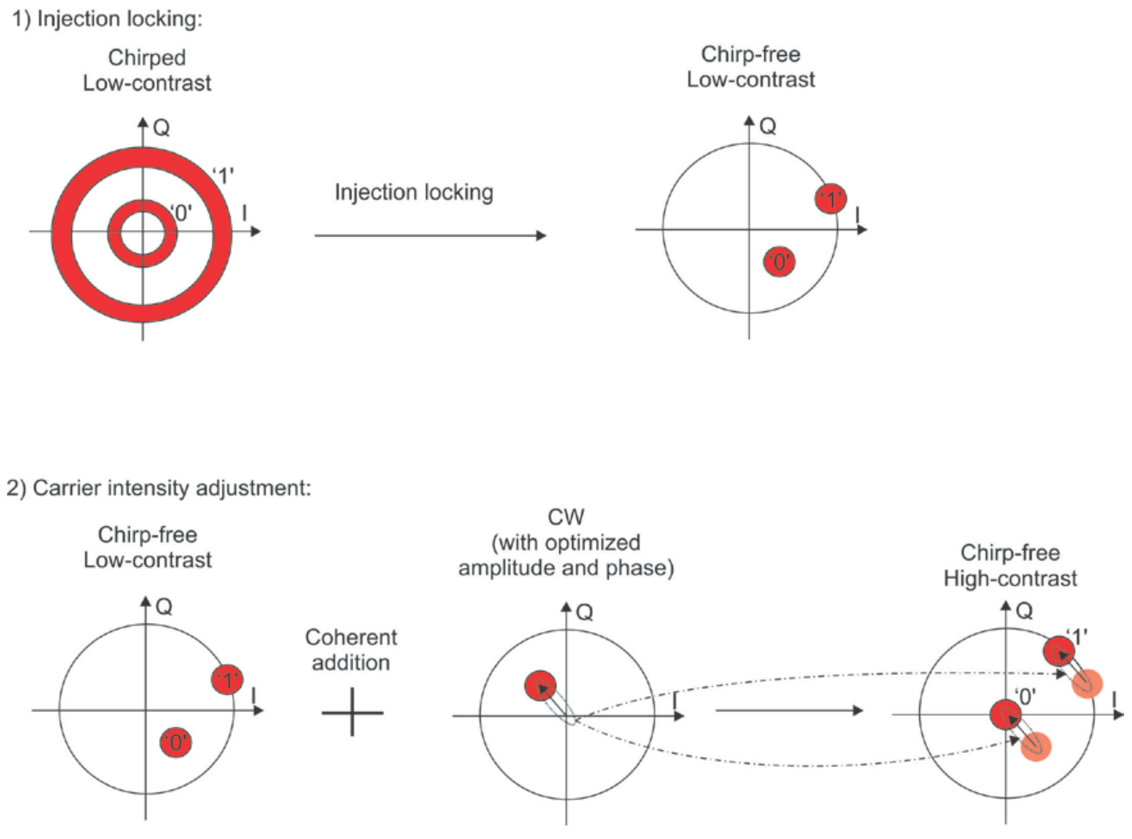


Figure 3. Principle of our method shown using constellation diagrams. First, the chirp is suppressed via injection locking. Subsequently, the modulation contrast is improved by interfering the injection-locked modulated laser output with a portion of the CW master.

3. EXPERIMENT

The experimental set-up is shown in Figure 4. The master laser is a tunable laser emitting 18 dBm of optical power. The optical part of the set-up consists of a Mach-Zehnder interferometer that has the slave laser in one arm and a fiber PZT-based stretcher in the other arm to adjust the relative phase of the slave laser output and the portion of the master signal that is combined with the slave to improve the modulation contrast. The slave laser is injection-locked via its front facet using an optical circulator. To adjust the injected power, an attenuator is used. Another attenuator is used to control amount of CW master that is combined with the slave laser output. The slave laser is modulated at 10 Gbit/s with pseudorandom bit sequence (PRBS) of 2^{31}-1 length. The output is characterized using high-speed sampling oscilloscope, optical spectrum analyzer and AC-coupled constellation analyzer. To maintain stable interference between the slave laser output and the portion of the master CW signal, a feedback control circuit is implemented that uses a small 20 kHz dither signal and subsequent lock-in detection.

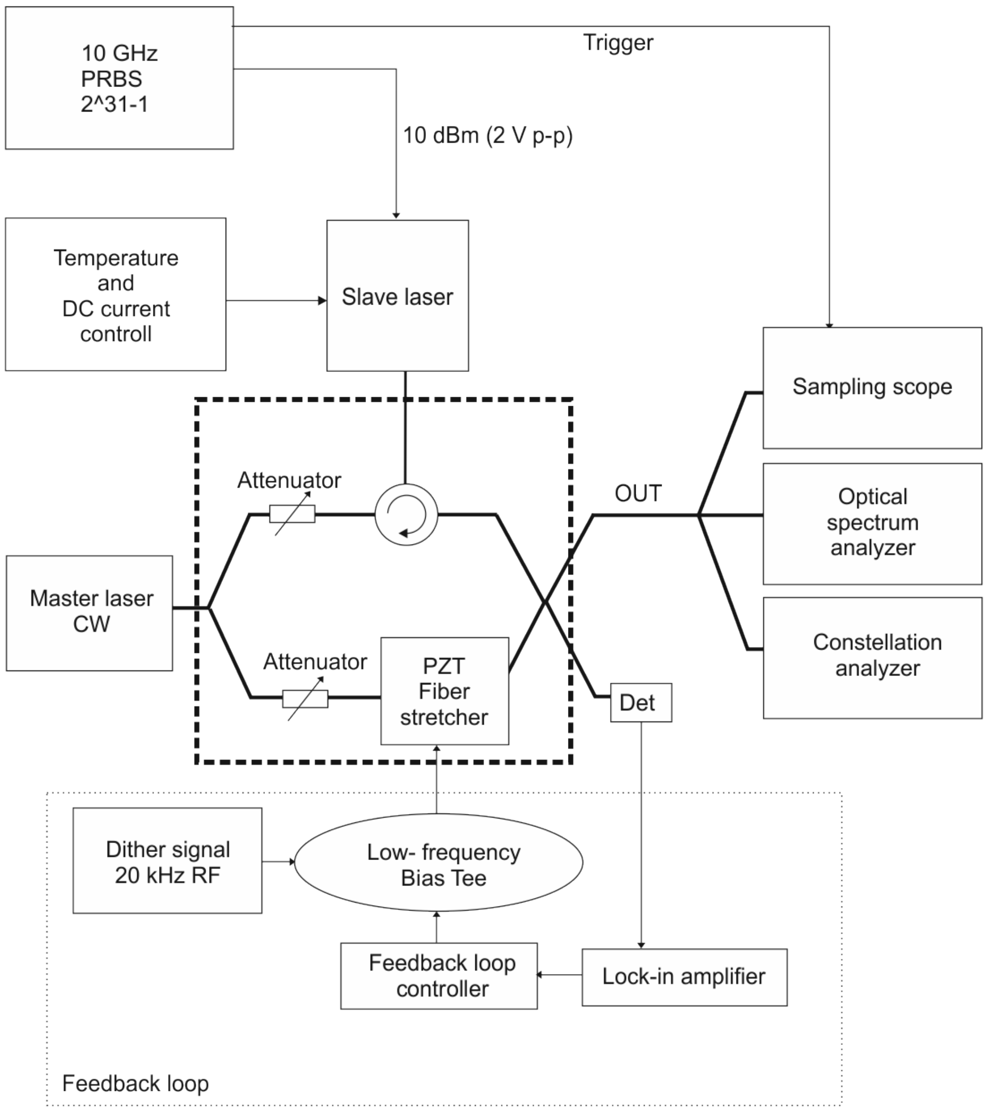


Figure 4. Experimental set-up

Figure 5 shows spectral traces when the portion of the master CW propagating in the lower arm of the Mach-Zehnder interferometer (Figure 4) is fully blocked, showing signal directly proportional to the slave laser output. We can observe that the free-running laser has very large chirp, which manifests itself by significant spectral broadening of the signal. This is hugely reduced via the injection locking. Following this experiment, we adjusted the amount of signal in the optical carrier by a proper (amplitude and phase) combination of the slave laser output with a portion of CW master light. The result measured with the optical spectrum analyzer is shown in Figure 6.

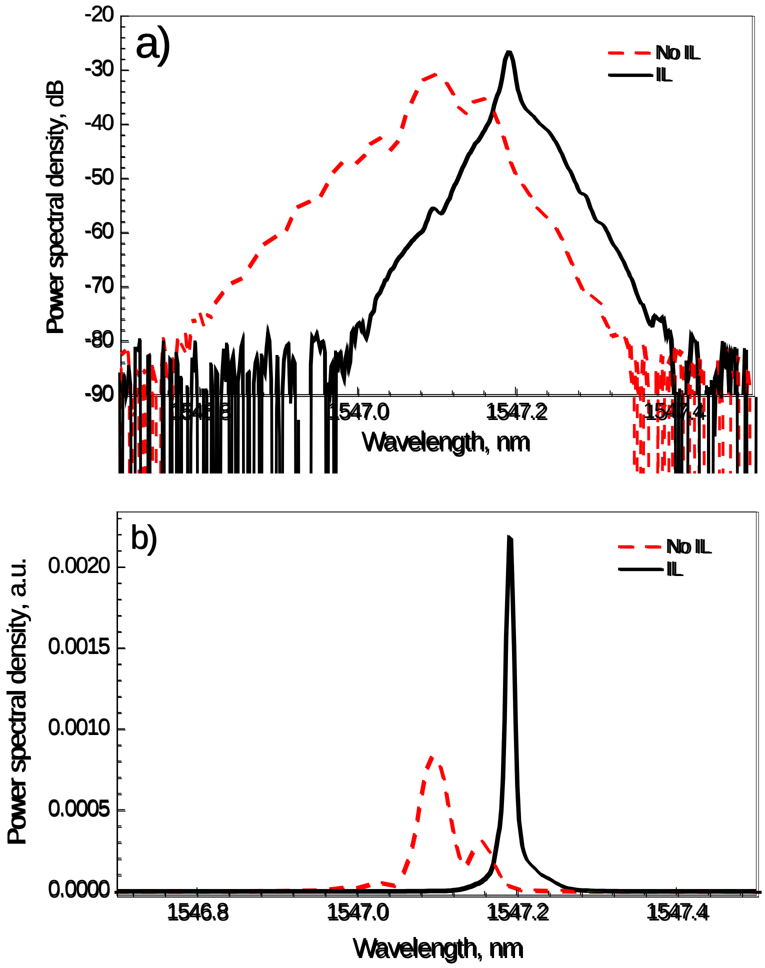


Figure 5. Spectral characteristics when the CW master light in the lower arm of the Mach-Zehnder interferometer (Figure 4) is fully blocked in the logarithmic (a) and linear (b) scales.

Eye diagrams measured with high-speed optical sampling oscilloscope are summarized in Table 1. We see distortion of the free-running directly-modulated laser that is greatly reduced under the injection locking. The injection-locked slave laser has already-acceptable contrast ratio of 6 dB. However, this is further improved after proper combination with the portion of the master CW. As shown in Table 1, contrast in excess of 10 dB was obtained. We believe this number could be further improved by better optimizing our feedback loop parameters and the loop filters involved.

To show the output is chirp-free, we characterized it using constellation analyzer that shows also the transitions between the two logical levels. The analyzer was AC-coupled and thus does not show exact position of the two points in respect to the zero, however, the measured result shown in Figure 7 clearly shows the signal is chirp-free with transitions happening in a straight line between the two constellation points.

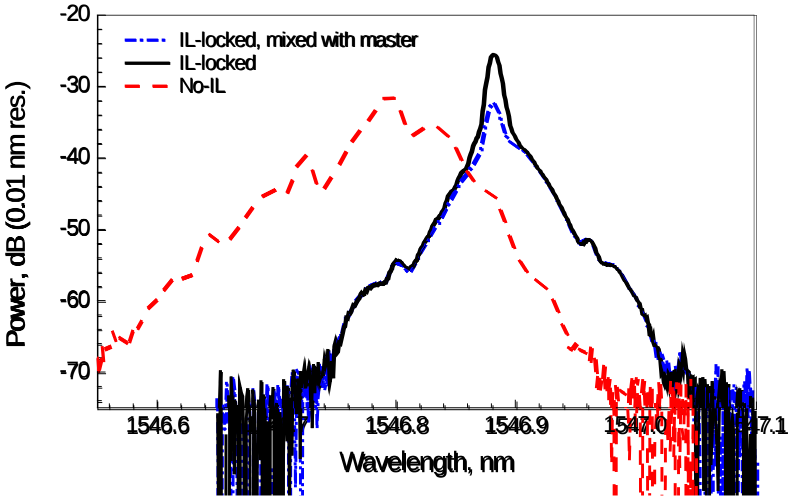
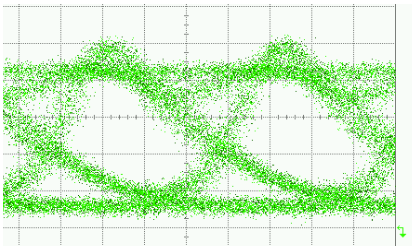
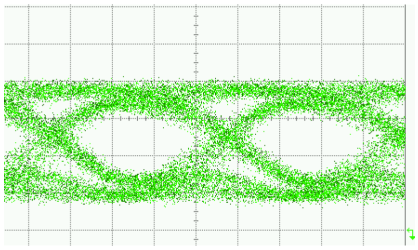
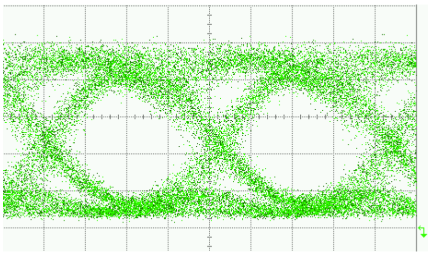
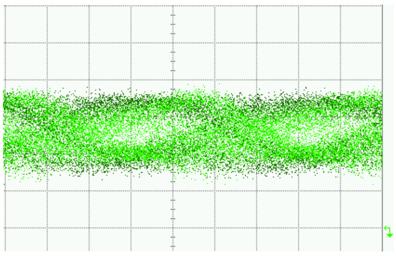


Figure 6. Spectral characteristics of the injection-locked slave (as shown in Figure 5) and of the injection-locked slave laser combined with properly adjusted portion of the CW master signal to reduce power in power carried by the optical carrier.

Table 1. Eye diagrams

Free-running slave 	Injection-locked slave, no master CW added 
Injection-lokced slave, CW master added, correct phase set on the PZT stretcher 	Injection-lokced slave, CW master added, the worst-case phase set on the PZT stretcher (eye maximally closed) 

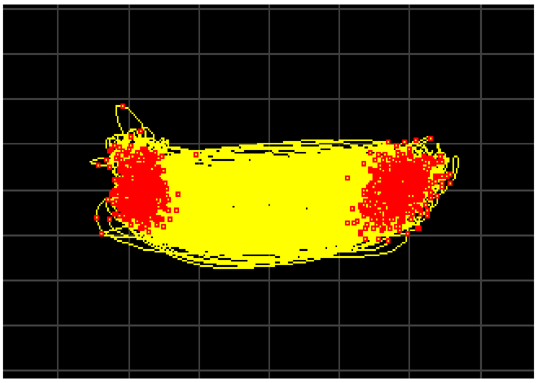


Figure 7. AC-coupled constellation diagram showing chirp-free operation of the injection-locked directly-modulated slave laser.

4. DISCUSSION AND CONCLUSIONS

Directly-modulated lasers are typically operated at limited extinction ratios (3-7 dB). Our method can suppress the chirp via injection locking and, at the same time, can improve the extinction ratio by destructively interfering the modulated signal with a small portion of the master laser, thereby mitigating two main limitations associated with the use of directly-modulated lasers for low cost on-off keyed communications. Finally, injection locking can significantly enhance the laser modulation bandwidth – e.g., in reference 3 a 3-dB bandwidth of 80 GHz was achieved. This would allow our scheme to operate at up to 160 Gbit/s. Even without any bandwidth enhancement, 40 Gbit/s operation should be achieveable, e.g., by using the lasers reported in reference 4.

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