The Effect of Optical Comb Spacing, Detuning and Injected Power on Optical Demultiplexing through Injection Locking

(Student Paper)

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ABSTRACT

We present a study on the effectiveness of optical injection locking as a method of demultiplexing narrowly spaced optical combs. Numerical and experimental results are presented, which show how the side mode suppression ratio of demultiplexed optical combs varies with respect to the optical comb spacing, injected optical power, and detuning.

Keywords: Injection locking, optical combs, photonic integration

1 INTRODUCTION

In order to continue the exponential growth internet traffic has seen in recent years, research has been focused on developing new optical communications infrastructures suitable for increased network bandwidth. Flexible or elastic optical networks have been proposed as a possible new architecture, in place of the old rigid wavelength division mutiplexing networks [1]. These flexible networks allow the optical bandwidth and modulation formats used to be dynamically adjusted, and have been made realisable due to advances in transmitting and recieving optical superchannels using narrowly spaced coherent optical combs [2]. As well as reducing power consumption and the number of individual components required, optical combs offer advantages such as allowing the WDM channels to be more densely packed, and simplifying the digital signal processing [3].

Photonic integration can further reduce the cost and power consumption involved with using these optical combs. Hence, much research has been focused on creating monolithically integrable comb sources and optical demultiplexers. Suitable comb sources with optical spacings between 4 GHz and 10 GHz have already been demonstrated [4], prompting the need to demultiplex combs with these spacings on chip. As arrayed waveguide gratings capable of demultiplexing these narrow combs have yet to be demonstrated on active material, current designs of such demultiplexers use optical injection locking [5], [6]. These demultiplexers are attractive as they amplify the output target comb line, and their locking range provides a tolerance to drift in the system.

In this paper, we investigate how the comb spacing effects the output side mode suppression ratio (SMSR) of such demultiplexers, both theoretically and experimentally. We show that for comb spacings close to the relaxation oscillation (RO) frequency, the SMSR sharply drops. We also find that while stronger injection strengths give larger locking bandwidths, the SMSR decreases with injection strength.

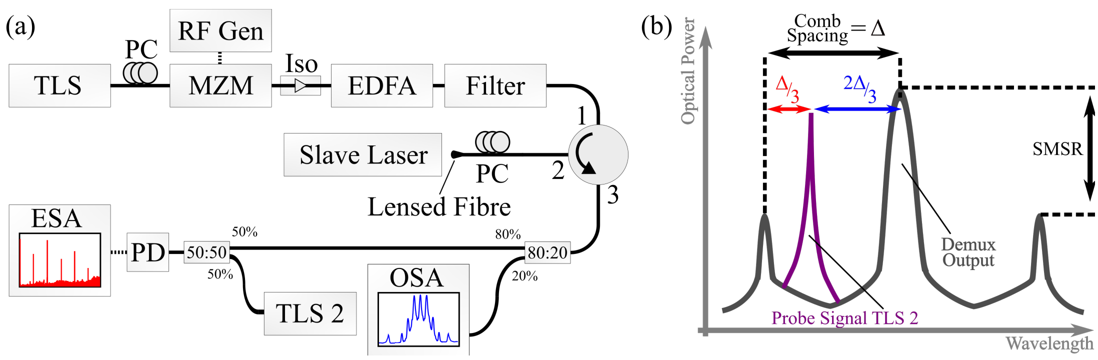

Figure 1. **(a)** The experimental setup used to perform the comb experiments. TLS: Tunable laser source, MZM: Mach zehnder modulator, PC: Polarisation controller, EDFA: Erbium doped fibre amplifier, OSA: Optical spectrum analyser, PD: Photodiode, ESA: Electrical spectrum analyser. **(b)** Illustration showing where the probe wavelength from the second TLS was located relative to the demultiplexed comb.

2 METHOD

The experimental set up used to investigate the effect of the comb spacing on the SMSR of the demultiplexed optical comb is presented in Fig. 1 (a). The slave laser was a single moded InP device lasing at approximately

1550 nm, with a free running SMSR of 40 dB at 90 mA. A circulator was used to collect the light from the slave laser output, which was monitored on an optical spectrum analyser (OSA). As the resolution of the OSA was insufficient to monitor the SMSR of demultiplexed combs with spacings below 5 GHz, the beat signal between the unlocked comb lines and a second tunable laser source (TLS) (or a probe TLS) was measured on an electrical spectrum analyser. In this way, the variation in the magnitude of the beat signal was used to monitor the strength of the comb's side modes. Figure 1 (b) shows how the lasing wavelength of the probe TLS was fixed relative to the comb. The probe TLS was tuned such that, for a comb spacing of Δ, there was a frequency separation of $\Delta/3$ between one of the unlocked side modes and the probe wavelength.

The experiment was also simulated using a rate equation model [7]. The rate of change of the complex electric field $\widetilde{E_s}(t)$ of the laser under the injection of the master laser's field $\widetilde{E_M}(t)$ is given by:

$$\frac{d}{dt}\widetilde{E_s}(t) = \left(i\omega_0 + \frac{1}{2}\left[G_N\left(N - N_{th}\right) - \frac{1}{\tau_p}\right]\right)\widetilde{E_s}(t) + \eta f_d \widetilde{E_M}(t), \tag{1}$$

where η is the coupling efficiency, f_d is the longitudinal mode spacing of the slave laser. All parameters and values used are given in table 1. We define the complex electric field $\widetilde{E_s}(t)$ of the slave laser as $\widetilde{E_s}(t) = E_s(t)e^{i(\omega_0 t + \phi_s(t))}$, where here $E_s(t)$ and $\phi_s(t)$ are the real amplitude and phase of the slave laser, and ω_0 is the angular frequency of the free running slave laser. The field of the master laser $\widetilde{E_M}(t)$ which couples to the slave laser's signal was defined as:

$$\eta f_d \widetilde{E_M}(t) = \sum E_j(t)e^{i\omega_j t}. \tag{2}$$

Here, $E_j(t)$ and ω_j are the field amplitude and angular frequency of the j-th comb line. Using the above definitions, equation (1) can be converted to an amplitude-phase representation:

$$\frac{dE_s}{dt} = \frac{G_N\left(N - N_{th}\right)E_s(t)}{2} + f_d\sum E_j \cos\left(\Delta\omega_j t - \phi_s(t)\right) \tag{3}$$

$$\frac{d\phi_s}{dt} = \frac{\alpha_H G_N\left(N - N_{th}\right)E_s(t)}{2} + f_d\sum \frac{E_j}{E_s}\sin\left(\Delta\omega_j t - \phi_s(t)\right) \tag{4}$$

In Eq. (3) and Eq. (4), $\Delta\omega_j$ is the difference in the angular frequency of the free running laser and the j-th comb line, and the amplitude of injected comb lines E_j is assumed not to vary in time. The carriers N are modelled as:

$$\frac{dN}{dt} = R_p - \frac{N}{\tau_s} - G_N\left(N - N_{th}\right)E_s(t)^2 - \frac{1}{\tau_p}E_s(t)^2 \tag{5}$$

where R_p is the pump rate, and τ_p and τ_s are the photon lifetime and carrier lifetime respectively.

TABLE 1. PARAMETERS USED IN THE MODEL.

G_N	$7.9 \times 10^{-13} m^3 s^{-1}$	Differential gain
ω_0	$3.798 \times 10^{14} rads^{-1}$	Slave laser natural frequency
R_p	$1.8 \times 10^{33} s^{-1}$	Pump rate (at threshold)
N_{th}	$2.91924 \times 10^{24} m^{-3}$	Threshold carrier density
α_H	3.5	Linewidth enhancement factor
τ_s	$2.0 \times 10^{-9} s$	Carrier lifetime
τ_p	$2.0 \times 10^{-12} s$	Photon lifetime
η	1	Coupling efficiency
f_d	$36 \times 10^9 Hz$	Longitudinal mode spacing of the slave laser

3 RESULTS

Results showing the effect of the comb spacing on the SMSR obtainable through demultiplexing with an injection locked slave laser are shown in Fig. 2 (a). The slave laser was locked to the centre line of a 3 line optical comb, with approximately zero detuning. The experimental results (plotted in black on the left axis) show the beat note between the probe TLS and the demultiplexed comb line as the comb spacing was varied. The results show the average beat note obtained over multiple tests, and the error bars indicate the maximum and minimum beat note strengths measured. As the comb frequency spacing varies, the beat note rises significantly around a comb spacing of 5 GHz. A rise in the beat note between the demultiplexed line and the probing signal implies that the output SMSR decreased, as the probe TLS had constant power. Simulated SMSR results are shown in red, plotted on the right axis in Fig. 2 (a). The dotted vertical line indicates the free-running relaxation oscillation (RO) frequency of the slave laser in experiment and theory, which was measured experimentally to be 4.375 GHz at bias of 90 mA. Both theory and experiment predict that as the frequency spacing of the optical comb approaches the RO frequency, the SMSR decreases. This dip in SMSR at the RO frequency is due to modulation caused by the unlocked comb lines. The unlocked comb lines weakly modulate the laser's carriers at the frequency of the comb spacing. While this modulation is small for large frequency spacings, closer to the RO frequency this modulation resonates with the natural resonance of the carriers in the slave laser, increasing the effect of the modulation. Neighbouring comb lines of the optical comb see far less loss as a result, causing the SMSR to decrease. As discussed in [8], fluctuations in the phase of the slave laser output due to the injected comb are also at a maximum at when the comb spacing approaches the RO frequency. Hence, optical comb spacings close to the RO frequency of the slave laser should be avoided for coherent applications.

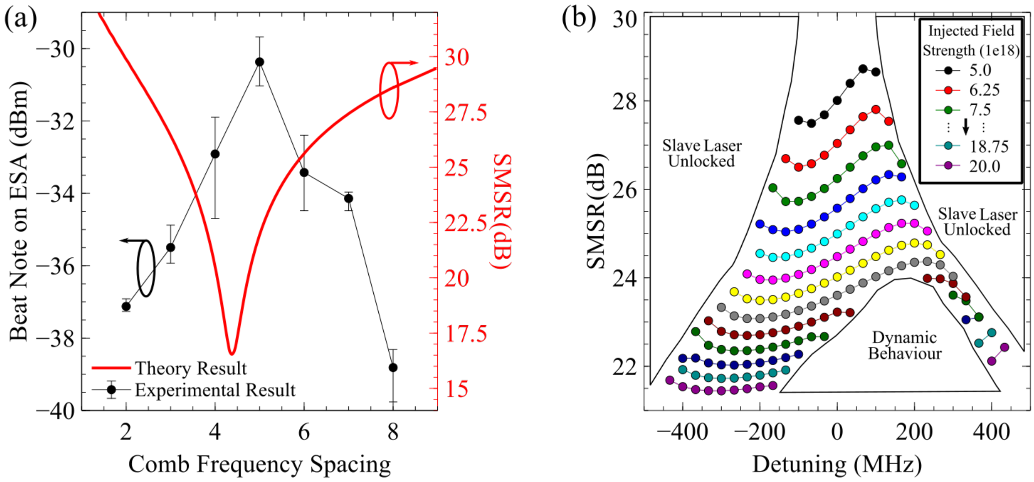

Figure 2. **(a)** Experimental results (left axis) showing the beat note of the unlocked comb line with the probe TLS versus comb spacing, with an inject power of $-8\ dBm$. Simulated SMSR (right axis) results for an injected field strength of 2.1×10^{18}, at 1.33 times threshold. **(b)** Simulated SMSR versus detuning. From top to bottom, optical power increases in steps of 1.25×10^{18} for a $10\ GHz$ spacing.

Figure 2 (b) presents simulated results, showing how the SMSR varies with injected power and detuning. As the injection locked slave laser has a locking bandwidth over which the slave laser is effective as a demultiplexer, the filter is less effected by external frequency drifts. This locking bandwidth depends on the injected optical power - a higher injected power gives larger bandwidths. As shown in Fig. 2 (b) however, increasing the injected optical power decreases the SMSR attainable. All injected powers chosen show positively detuning the slave laser from the injected signal gives a higher SMSR than negatively detuning. For weak injection strengths, a slight change in detuning may rapidly change the SMSR. As the injection strength and locking width increase, the variation in SMSR with detuning is less pronounced. For higher injection strengths, the slave laser's output can enter a region of dynamical behaviour, marked on the bottom of Fig. 2 (b). Within this region, the slave laser is no longer effective as a demultiplexer. Studies on the dynamics within this region are currently being completed.

4 CONCLUSION

We present experimental and theoretical results which show how the frequency spacing of the injected optical comb effect the SMSR of the demultiplexed comb. Our results indicate that comb frequency spacings close to the relaxation oscillation frequency of the slave laser have significantly worse SMSRs than for large frequency spacings. Variation in the output SMSR versus detuning and injected power was also investigated theoretically. It was found that the although increasing the optical power increases the demultiplexer's bandwidth, higher powers decrease the SMSR attainable.

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