Bandwidth Enhancement by Optical Amplitude and Phase Modulation of Injection-Locked Semiconductor Lasers

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***Abstract*— We experimentally demonstrate optical modulation of injection-locked lasers, resulting in a resonant amplification of the transmitted signal. We demonstrate both phase modulation and amplitude modulation, comparing the two formats. For amplitude modulation, we enhance the 3-dB bandwidth of a 25-GHz electro-optic modulator to 59 GHz. For phase modulation, we enhance the 3-dB bandwidth of a 17-GHz phase modulator to 53 GHz. Additionally, we demonstrate the system's dynamic tunability up to resonance frequencies >100 GHz.**

I. INTRODUCTION

The bandwidth of a directly-modulated laser is typically determined by the laser's relaxation oscillation (resonance) frequency [1, 2]. The laser's 3-dB bandwidth will usually be a few GHz higher than its resonance frequency. Optical injection locking (OIL) has been shown to increase the resonance frequency and bandwidth of a directly-modulated semiconductor laser [3-5]. Previously, we have demonstrated resonance frequencies up to 72 GHz and bandwidths > 40 GHz [6]. However, in the injection-locked laser, the resonance frequency does not necessarily determine the bandwidth, as it does for the free-running, directly-modulated laser. Specifically, the OIL laser, in specific circumstances, can experience a low-frequency pole that can severely limit its response [6, 7]. This pole is independent from the RC parasitics inherent in the laser packaging and can be derived from the laser dynamics.

Several works in the past have performed optical modulation of injection-locked lasers. However, they focus on low-injection regimes [8] and/or the applications of amplitude modulation suppression [9-11] or FM discrimination [12]. Previously, we have shown various methods of modulation on the master laser (ML) [13]. In the master amplitude modulation optical injection locking (MAM-OIL) system, rather than directly-modulating the slave laser (SL), the master laser light is amplitude modulated before being injected into the slave (Fig. 1) [13, 14]. Alternatively, in master phase modulation OIL (MPM-OIL), the master light is phase modulated before injection. In this paper, we utilize the enhanced laser dynamics of OIL to selectively enhance a dynamically-tunable bandwidth of: 1) an amplitude-modulated (AM) 2) and a phase-modulated (PM) optical signal. We show that these techniques do not suffer from the low-frequency pole, but follow their own unique set of dynamics. Utilizing these techniques, we demonstrate bandwidths of >59 GHz for MAM-OIL and 53 GHz for MPM-OIL. Recently, it has been shown that the optical modulation can be cascaded to further extend the bandwidth [14]. This is applicable to both master AM and PM techniques. Additionally, we show that the system can be dynamically tuned to enhance frequency bandwidths centered on resonances > 100 GHz.

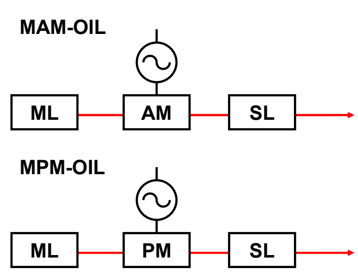

Figure 1. Schematic illustrating the MAM-OIL and MPM-OIL configurations. The source of the amplitude or phase modulation are not limited to discrete components.

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II. EXPERIMENT

The experimental setup for both MAM-OIL and MPM-OIL is shown in Fig. 2. Here, the MAM is created by a zero-chirp, $LiNbO_3$ electro-optic modulator (EOM). Note that the technique is not limited by the modulation source type and can be integrated with either master or slave. The MPM is created by a $LiNbO_3$ phase modulator. The slave laser is a 1550 nm distributed feedback laser. A polarization controller (PC) is used to optimize the input polarization to the $LiNbO_3$ modulators. The output of the modulators is amplified by an Erbium-doped fiber amplifier (EDFA). Another PC is used to optimize the coupling polarization into the slave laser. An isolator (arrow) is used to prevent optical feedback to the master laser. The injection is accomplished by an optical coupling head with 3-dB insertion loss. The modulated slave laser light is coupled to another optical head on the opposing facet. It is then optically amplified, then detected by a photodetector. Electrical modulation and detection are performed by a vector network analyzer. Detection of the phase modulation was performed by the AM/PM separation technique described by Sorin, *et al.* [15]. We used a 0.95 nm bandwidth tunable optical filter (Santec OTF-920) after the slave laser output to obtain frequency discrimination at both quadrature points of the filter.

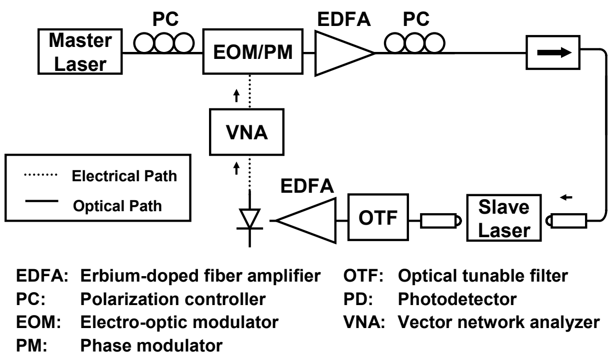

Figure 2. Experimental setup of the MAM-OIL and MPM-OIL system. An EOM is used in the MAM-OIL case while a PM is used in the MPM-OIL case.

The free-running frequency response of the slave laser, biased at 2.4 times threshold, is shown in Fig. 3. Its resonance frequency (f_{RO}) is 3 GHz and its 3-dB bandwidth (f_{3dB}) is 4 GHz. We then injection lock the slave laser. The injection ratio, R_{inj}, (defined as the optical power ratio of the master and free-running slave, measured at the injected slave laser facet) was 3 dB. The detuning frequency, Δf_{det}, (defined as the frequency difference between master and free-running slave) was +12.4 GHz. We show the results of a directly-modulated OIL laser in Fig. 3 (DM-OIL). The enhanced f_{RO} was 30 GHz. Note the drop in response starting close to DC, resulting in a 3-dB bandwidth of ~1 GHz, much lower than its resonance frequency. This is not due to the laser RC parasitics, as the 3-dB frequency of the RC parasitics is >5 GHz.

For the MAM-OIL case, the conditions were kept the same as for the directly-modulated OIL case. The only difference was that an EOM with a f_{3dB} = 25 GHz was used for the modulation source. The resultant amplitude modulation upon the slave is shown in Fig. 3 (labeled MAM-OIL). Note the 17-dB dip in the response near DC. This low-frequency suppression is characteristic of the technique and appears for most OIL conditions. The magnitude of the dip is reduced for higher injection ratios and more negative detuning frequencies. For the MPM-OIL case, again, all conditions remained constant. However, a phase modulator with a f_{3dB} = 20 GHz was use as the modulation source. The resultant phase modulation upon the slave is shown in Fig. 3, labeled (MPM-OIL). Note that there is no dip at DC, and the response looks similar to that of a free-running, 2-pole laser (i.e. classic damped oscillator). The fitted resonance frequency for all OIL cases were found to be 30 GHz, and the fitted damping factors were all calculated to be within 3-4 GHz. Hence, each OIL modulation scheme shares the same resonance and damping. However, the response between DC to resonance differs quite dramatically.

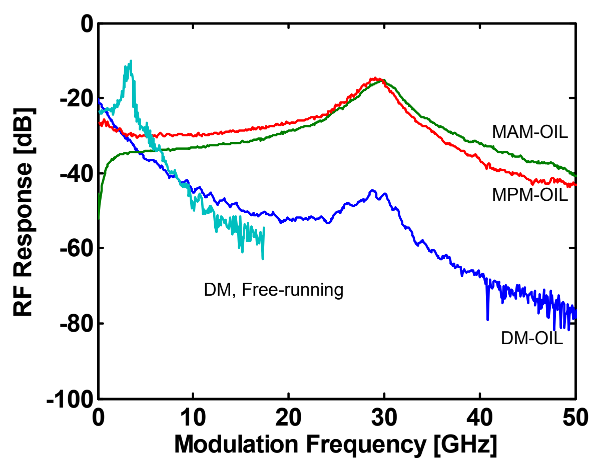

Figure 3. Frequency response of an OIL laser under various modulation schemes. OIL conditions (Δf_{det}, R_{inj}) are held constant for all cases. DM-OIL: direct modulation of the OIL laser. Note the drop in response starting near DC. The RC 3-dB frequency is >5 GHz. MAM-OIL: note the dip in DC response. MPM-OIL: relatively flat response up to resonance. DM, Free-running: Free-running shown for comparison.

A. *MAM-OIL*

If we increase the injection locking parameters, we can optimize the enhanced EOM response. Fig. 4 shows the frequency response of the EOM, with a f_{3dB} = 25 GHz. All response curves are normalized for cables, network analyzer, and photodetector response. The EOM exhibits a resonant notch at 55 GHz, possibly due to surface mode coupling or other effects. Note that this is not a fundamental limitation of the EOM and may be engineered notch-free. By injection locking the slave laser with the modulated light, we can tune the enhanced resonance of the OIL system to compensate for the notch, resulting in an enhanced f_{3dB} = 59 GHz (line (a), Fig. 4). The OIL conditions were R_{inj} = 8 dB and Δf_{det} = +27 GHz. The tunability of the resonance can be used to create a broad resonance that can compensate for the typically slowly-decreasing response of an EOM, resulting in a flatter frequency response (line (b), Fig. 4) (R_{inj} = 8.5 dB and Δf_{det} = +30 GHz). We achieve a relatively flat response over >70

GHz bandwidth, interrupted only by the 55 GHz resonant notch caused by the EOM itself. Note that both MAM-OIL cases in Fig. 4 do not show the characteristic dip at DC, found in the MAM-OIL response of Fig. 3. This is possibly due to the fact that the laser is at a much higher injection ratio and also pulled away from the positive detuning edge, where the most severe DC suppression occurs.

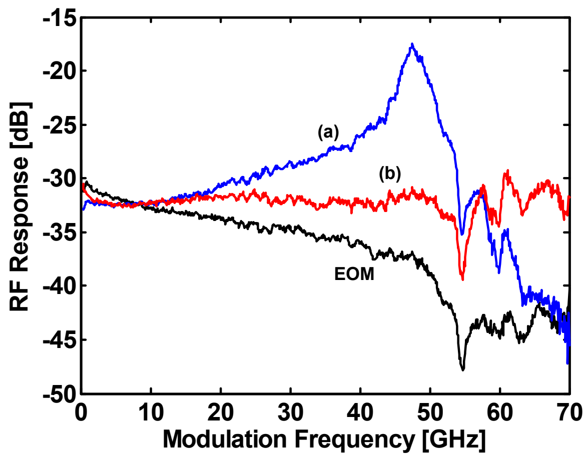

Figure 4. Frequency response of EOM (f_{3dB} = 25 GHz) and EOM + MAM-OIL for two different bias conditions: (a) R_{inj} = 8 dB Δf_{det} = +27 GHz; (b) R_{inj} = 8.5 dB, Δf_{det} = +30 GHz. (a) is optimized for 3-dB bandwidth (f_{3dB} = 59 GHz) while (b) demonstrates >70 GHz flatness (aside from notch at 55 GHz).

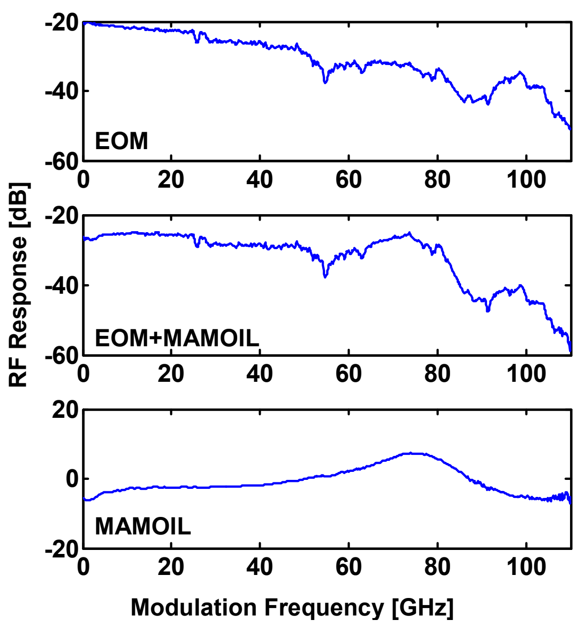

Figure 5. Frequency response of EOM (top) and EOM + MAM-OIL (middle). The difference of these two responses corresponds to the optical response of the MAM-OIL laser by itself (bottom).

Fig. 5 shows the MAM-OIL tuned to the maximally-flat condition. In the three panels, we show the EOM response by itself, the EOM injected into the slave (MAM-OIL), and the difference of the top two responses, which represents the normalized response of the MAM-OIL laser by itself. The middle panel demonstrates a relatively flat response up to 76 GHz, aside from the dips in the frequency response due to the EOM itself around 55 GHz. From the normalized response in the bottom panel, we can clearly see a resonance frequency of 75 GHz. By tuning the detuning frequency, the resonance frequency can be tuned over a very wide range. Fig. 6 shows the optical transmission response of the MAM-OIL laser, by subtracting the EOM response from the EOM+MAM-OIL response. Again the characteristic dip at DC of 5-10 dB is seen in the each normalized response in Fig. 6. Here, we changed Δf_{det} from 7 to 32 GHz, resulting in resonance frequencies of 73 to 107 GHz, respectively. To the authors' knowledge, this is the first time that resonance frequencies > 100 GHz have been electrically measured in semiconductor lasers.

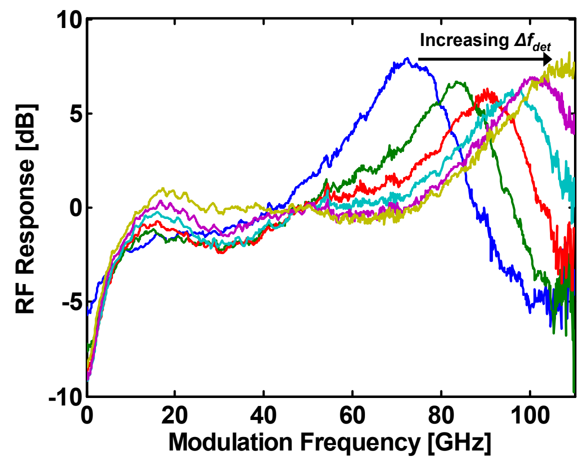

Figure 6. Optical response of MAM-OIL for various detuning

B. MPM-OIL

We then performed similar experiments for the MPM-OIL configuration. Fig. 7 shows the frequency response of the MPM-OIL system for various injection conditions (Fig. 7, lines (a)-(c)). As with all modulation schemes, including direct modulation, the resonance frequency increases with detuning frequency and injection ratio. The response of the PM is shown for reference (Fig. 7, line PM). The noise at DC is inherent in the AM/PM separation technique. Since the actual detected value is proportional to frequency modulation response, a factor of $1/f_m$ (where f_m is the modulation frequency) was applied to the signal to obtain the phase modulation response. The bandwidths of the PM, (a), (b), and (c) are 20, 36, 40, and 53 GHz, respectively. Hence, bandwidth enhancement can be obtained through this modulation scheme as in MAM-OIL. Additionally, the MPM-OIL system does not exhibit the low frequency suppression as in the case of MAM-OIL.

In Fig. 8, we show the optical response of the MPM-OIL system, after removing the response from the PM. Here, we scan the detuning frequency across the locking range (Δf_{det} = -30 to 0 GHz) for a fixed injection ratio (R_{inj} = 3 dB). Note the absence of the low frequency suppression that was found in the MAM-OIL case. The frequency responses more closely matches that of a classic damped oscillator.

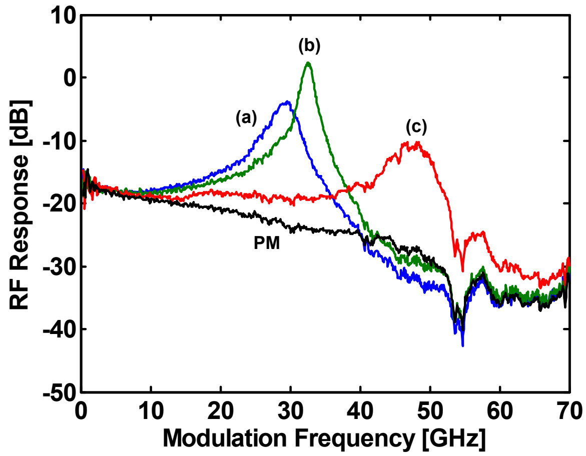

Figure 7. Frequency response of MPM-OIL for different injection conditions: (a) R_{inj} = 3 dB Δf_{det} = +12 GHz; (b) R_{inj} = 3 dB, Δf_{det} = +18 GHz; (c) R_{inj} = 4 dB, Δf_{det} = +25 GHz. The response of the phase modulator is shown for reference (PM). The bandwidths for the PM , (a), (b), and (c) are 20, 36, 40, and 53 GHz, respectively.

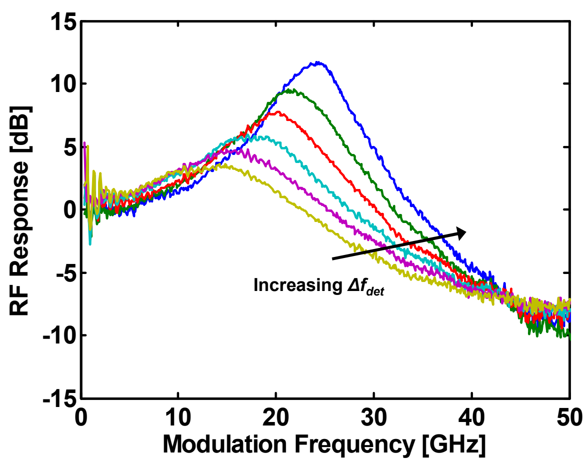

Figure 8. Optical response of the MPM-OIL system for various detuning frequencies (Δf_{det} = -31 to 0 GHz), demonstrating tunability of resonance frequency, from 13 to 25 GHz.

III. CONCLUSION

We have demonstrated optical amplitude and phase modulation of an injection-locked semiconductor laser. Both techniques are not limited by the low-frequency pole that dominates the bandwidth in the positive detuning frequency regime of directly-modulated OIL lasers. Furthermore, the slave laser's RC parasitics no longer limit the system's performance. Rather, we are relieved of the concerns of engineering low laser parasitics and can focus our interest to the electrical parasitics and performance of the modulation source. The benefit of the injection-locked laser is in providing an enhancement of bandwidth that can be dynamically tuned to different frequency bands. The MAM-OIL is a simple technique, requiring no coherent detection. However, in certain regimes, namely low injection ratios and positive detuning frequencies, it exhibits a low frequency suppression. The MPM-OIL technique is notably more complex in detection. However, in the positive detuning frequency range, it does not exhibit a low frequency suppression. We have demonstrated bandwidth enhancement up to 59 GHz for MAM-OIL and 53 GHz for MPM-OIL. These are enhancements of over 2 times the original bandwidth of the modulation source. The technique of MAM-OIL and MPM-OIL has the potential to be used as an all-optical equalization technique for next-generation 100 Gbps or broadband analog systems or as an ultra-high frequency, dynamically-tunable bandpass filter/amplifier.

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