Amplitude and Frequency Modulation of the Master Laser in Injection-Locked Laser Systems

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Abstract — **We explore the effects of modulating the master laser in injection-locked systems. We experimentally and theoretically discovered an intrinsic conversion of master FM into slave AM. We have *modified the current theory to model the frequency* response for residual amplitude modulation (RAM) suppression, FM efficiency, and FM-to-AM conversion.**

I. Introduction

The dynamic response of semiconductor lasers under strong optical injection locking conditions has received increasing interest [1-3]. Enhancement of modulation bandwidth, and suppression of nonlinear distortions and relative intensity noises (RIN) have been reported. Most of the previous studies on optical injection-locking have focused on the modulation of the slave laser. Modulation of master lasers has many interesting potential applications. Intuitively, the slave laser frequency would follow that of the master laser, while its intensity is weakly dependent on the master laser power. Potentially, this can be used to produce frequency modulation (FM) and/or suppress residual amplitude modulation (RAM). Alternatively, it can be used to lock the local oscillator in coherent analog optical links.

In this paper, we present a systematic study, both experimentally and theoretically, of the effects of master laser modulation on the slave laser. We found that FM can be preserved, up to the resonance peak and even for relatively weak injection ratios. Additionally, AM is suppressed proportionally to the injection ratio. We also discovered that pure master FM converts not only to slave FM, but also significantly creates slave AM. This novel conversion technique has a wide range of potential applications. The bandwidth of these effects are extended by resonance frequency enhancement in the strong-injection regime.

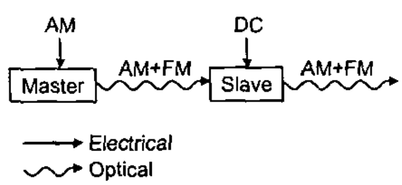

Fig. 1. Schematic of injection-locking with master laser modulation. Master modulation results in slave modulation.

II. Experiment

In injection-locked laser systems, a master laser injects light into a slave laser, thus modifying the slave's characteristics. Typically, we modulate the system by applying a modulating current (called direct modulation, or DM) on the slave. Alternatively, as shown in Fig. 1, we can apply DM on the master laser. Due to the chirping effect, the master output contains both FM and AM components, which are then injected into the slave. This modulation causes the slave to also produce AM and FM. Both injected AM and FM components play a part in creating AM and FM on the slave.

RAM suppression (AM to AM) and FM efficiency (FM to FM) have already been demonstrated in FM spectroscopy systems [4]. In this section, we experimentally demonstrate FM-to-AM conversion (FM to AM). We define FM-to-AM conversion as the conversion of injected FM into slave AM. The experimental setup is shown in Fig. 2. The master laser is a frequency-tunable diode laser and the slave laser is a 1550 nm distributed feedback (DFB) laser. We follow the master laser with a variable attenuator, polarizer and phase modulator (PM). The master light is injected into the slave via a circulator. The slave output is taken from the same side as injection. We obtain frequency response data via a network analyzer. We modulate the system at two different points: I. we modulate the master laser using a $LiNbO_3$ PM, which produces pure FM injection light; II. we directly modulate the slave laser. The same RF power is used on both modulation points. Fig. 3 shows the experimental results. The network analyzer's photodetector only senses slave AM and therefore the slave FM is decorrelated from these results. *AM on Slave (unlocked)* shows the direct modulation frequency response of the laser without injection. *AM on Slave (locked)* shows the characteristic enhanced resonance frequency due to injection locking. *FM on*

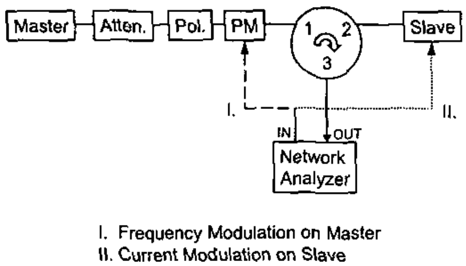

Fig. 2. Schematic of experimental setup for measuring FM-to-AM conversion and direct modulation.

master (unlocked) shows the effect of the master FM on the slave AM in the unlocked state (not injection-locked). Since the FM is not correlated to the AM in this case, the frequency response is essentially the noise of the network analyzer system. *FM on Master (locked)* shows FM-to-AM conversion for the injection-locked system. The FM-to-AM conversion is proportional to the modulation frequency and therefore there is less crosstalk for lower modulation frequencies and more for higher frequencies. Below resonance, the AM due to FM-to-AM conversion is much smaller than the AM due to direct modulation. At resonance, the FM-to-AM conversion magnitude is about 10 dB below the direct modulation and is a significant effect. Above resonance, the crosstalk effect is almost equal to the direct modulation.

Fig. 4 shows the FM-to-AM conversion for various injection ratios. We can compare this to our theoretical results, found in Fig. 5. The general response line features match up quite well, although the injection ratios are different, due to the fact that the real laser is a DFB rather than a Fabry-Perot, which is used in the theory. As also with direct modulation, the resonance frequency for FM-to-AM conversion is enhanced for larger injection ratio.

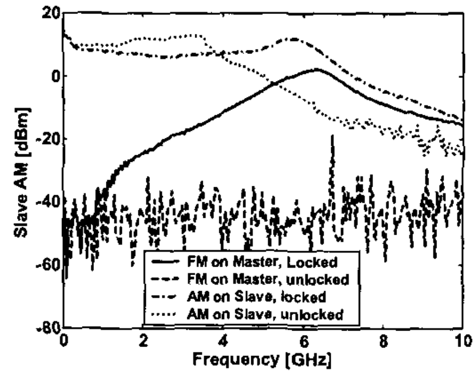

Fig. 3. Slave AM due to different modulation sources. FM-to-AM conversion and direct modulation are shown.

III. THEORY

A. Analysis

In order to analyze the effects of master laser modulation, we perform a small-signal linearization of the laser rate equations with injection [5]. However, this analysis contains only one driving term: current modulation on the slave. We modify the injection term, E_i (typically taken as a constant with frequency detuning) to include AM and FM driving terms:

$$E_i(t) = A_i(t)e^{-i\Omega t - i\theta(t)} \tag{1}$$

where $A_i(t)$, Ω, and $\theta(t)$, are the AM, detuned frequency, and PM (which translates to FM through a time derivative) of the master laser field, respectively. We then separate the slave amplitude and phase into two separate rate equations and then perform small-signal linearization. Our solution is similar to that found in [5], however it contains two additional driving terms: the master AM and the master PM. The final form of the

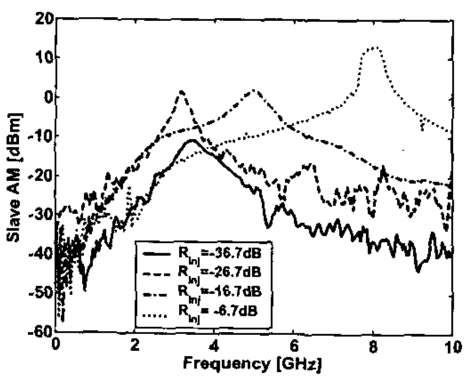

Fig. 4. Experimental FM-to-AM conversion for various injection ratios

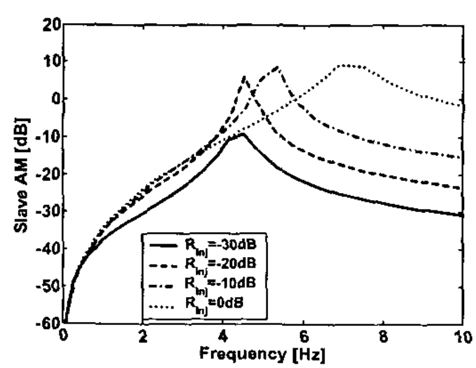

Fig. 5. Theoretical FM-to-AM conversion for various injection ratios

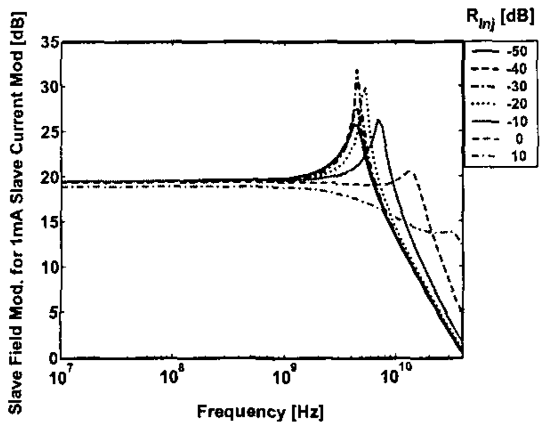

Fig. 6. Direct modulation for various injection ratios. Driving source: Current modulation on slave. Measured output: Optical AM on slave.

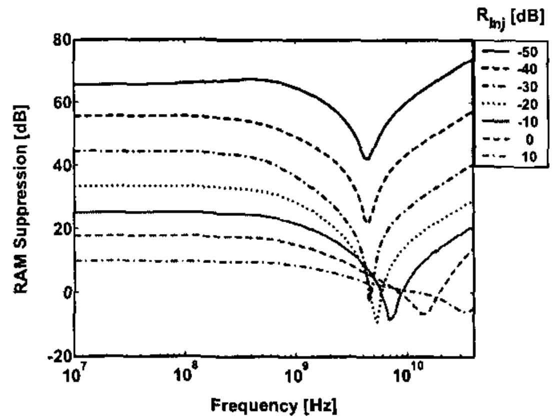

Fig. 7. RAM suppression for various injection ratios. Driving source: Optical AM on master. Measured output: Optical AM on slave.

matrix equations are:

$$\begin{bmatrix} m_{11}-s & m_{12} & m_{13} \\ m_{21} & m_{22}-s & m_{23} \\ m_{31} & m_{32} & m_{33}-s \end{bmatrix} \begin{bmatrix} \Delta A \\ \Delta \Phi \\ \Delta N \end{bmatrix} = \begin{bmatrix} -\eta_i \cos\varphi_0 \\ \eta_i \frac{1}{A_0}\sin\varphi_0 \\ 0 \end{bmatrix} \Delta A_i + \begin{bmatrix} -\eta_i A_{i0} \sin\varphi_0 \\ -\eta_i \frac{A_{i0}}{A_0}\cos\varphi_0 \\ 0 \end{bmatrix} \Delta\theta + \begin{bmatrix} 0 \\ 0 \\ -\frac{\eta}{eV} \end{bmatrix} \Delta I \tag{2}$$

Here, there are three separate driving terms: ΔA_i, $\Delta\theta$, and ΔI. The third driving term, ΔI, should be recognized as the direct modulation term, and can be commonly found in literature [5,6]. The first and second driving terms are the master's AM (ΔA_i) and PM ($\Delta\theta$). By choosing one of the three terms and setting the other two to zero, we can calculate that driving term's effect on the modulation of the slave field amplitude (ΔA), phase ($\Delta\Phi$), and carrier density (ΔN).

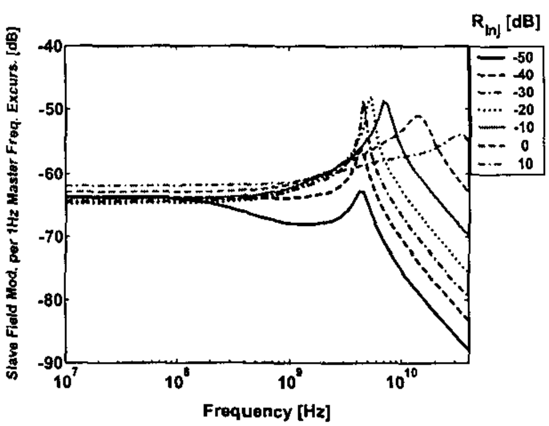

Fig. 8. FM-to-AM conversion for various injection ratios. Driving source: optical FM on master. Measured output: optical AM on slave.

B. Results

If we choose one output term and one driving term, we can take their ratio and from Eq. 2 determine its frequency response. There are 3 output and 3 driving terms, giving us 9 different ratios. The typical ratios found in literature are $\Delta A/\Delta I$ (DM to AM) and $\Delta\Phi/\Delta I$ (DM to FM), which can be used to determine the direct modulation frequency response and frequency chirp, respectively. Fig. 6 shows the frequency response from direct modulation for a typical edge-emitting laser, whose parameters we will use throughout this paper. The family of curves corresponds to varying injection ratios (R_{inj}). As observed in the literature [1,6], the resonance peak is enhanced for higher injection ratios.

If we explore the ratio, $\Delta A_i/\Delta A$ (AM to AM), we can observe how the master AM affects the slave AM. This ratio is proportional to residual amplitude modulation (RAM) suppression, which is defined as the degree of

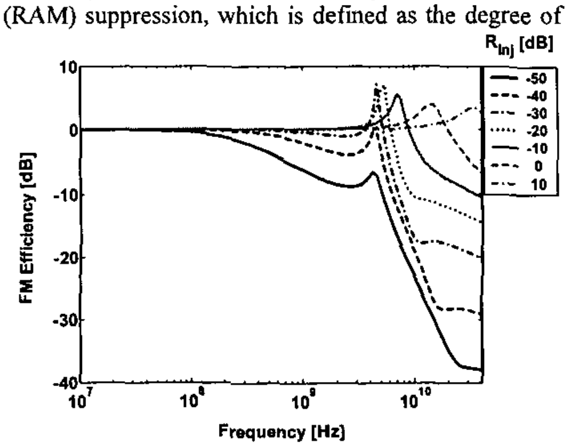

Fig. 9. FM Efficiency for various injection ratios. Driving source: optical FM on master. Measured output: optical FM on slave.

suppression of optical AM as it is transferred from master to slave. If we are interested in only the FM component of a signal that contains both AM and FM, RAM suppression may be useful in removing the unwanted AM. For example, this technique has been used in FM spectroscopy [4]. Fig. 7 shows the frequency response of RAM suppression for our sample laser. For smaller injection ratios, the suppression is greater, attesting to the fact that the master only injects small amounts of light into the slave's photon reservoir. At resonance, the suppression actually goes negative for higher injection ratios, which corresponds to an AM enhancement.

We can also determine the effect of master FM on both the AM and FM of the slave, through the ratios $\Delta A_i/\Delta\theta$ (FM to AM) and $\Delta\Phi/\Delta\theta$ (FM to FM), respectively. The first is proportional to FM-to-AM conversion; it shows a coupling between the master FM and the slave AM. This can be used as a FM discriminator or, in other applications, it may lead to unwanted AM, as in FM spectroscopy [4]. Fig. 8 shows the frequency response of the slave amplitude per Hertz of master frequency excursion. Fig. 5 shows the frequency response of the slave amplitude per radian of phase modulation excursion, and is related to Fig. 8 by the modulation frequency. Our theory (Fig. 5) predicts our experimental evidence of FM-to-AM conversion quite well.

The second term, called FM efficiency, shows how well the master FM is mapped onto the slave FM. This may be useful for preserving an FM signal from one laser to another. Fig. 9 shows the frequency response for FM efficiency. Note that for low frequencies, the FM efficiency is 0dB, which means that the slave laser is exactly tracking the detuned frequency of the master. At resonance, the slave actually overshoots the master's frequency for certain injection ratios. At higher frequencies, the slave's dynamics are too slow to track the master's frequency fully, hence the FM efficiency rolls off.

IV. CONCLUSION

We investigated the effects of applying modulation to the master laser in injection-locked systems, both experimentally and theoretically. We experimentally verified a novel phenomenon, FM-to-AM conversion, where the FM on the master laser is converted into AM on the slave laser. We show this to have a significant effect on the slave AM for high modulation frequencies, on the order of magnitude to direct modulation gain. Experimental evidence also shows that the FM-to-AM conversion is negligible for frequencies below resonance. We modified the existing small-signal analysis theory for injection-locked lasers to include driving terms for the master AM and FM. Using this model, we show the frequency response for RAM suppression, FM efficiency, and FM-to-AM conversion. RAM suppression is shown to be inversely proportional to the injection ratio. FM efficiency is shown to have a 1Hz-to-1Hz frequency excursion from master to slave, for frequencies up to the resonance point. FM-to-AM conversion is verified theoretically and shown to fit quite well with our experimental data. The bandwidth of all these effects is shown to increase, along with the enhancement of the resonance frequency, for higher injection ratios.

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