Bandwidth Enhancement of Electro-absorption Modulated Lasers by Optical Injection Locking

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***Abstract*—** We experimentally demonstrate bandwidth enhancement of an optically-injection-locked integrated electro-absorption modulator (EAM) and laser in an inverted configuration. The injected light is modulated by the EAM and enhanced by the injection locking dynamics. The 3-dB bandwidth of the EAM was increased from 8GHz to >40GHz.

In many optical telecommunications applications, it is desirable for the transmitter to exhibit a very large bandwidth electro-optic effect. This is necessary for transmitting signals with large information content. In semiconductor lasers, the modulation bandwidth is typically related to its resonance frequency. Optical injection locking (OIL) has been shown to enhance the resonance frequency of the directly-modulated injection-locked laser [1, 2]. However, the bandwidth does not follow the same simple relationship to the resonance frequency as does a free-running laser. Specifically, the OIL laser, in certain bias conditions, experiences a low-frequency roll-off that can severely limit its bandwidth [3]. Recently, we developed an alternate OIL method that, rather than directly modulating the slave laser, the master laser light is modulated *before* injection [4, 5]. The injection-locked slave serves to enhance the modulated light and can greatly increase its bandwidth. This method does not exhibit the low-frequency roll-off of the direct-modulation case and additionally does not suffer from the electronic parasitics of the slave laser and its packaging. The modulation of the master can be accomplished in a variety of ways: directly modulating the master laser or by electro-optic modulator (EOM) on the continuous-wave (CW) master light. The advantages of each are that with the EOM, the initial bandwidth of the EOM can be much higher than a directly-modulated laser; however, the directly-modulated laser reduces the number of discrete components by removing the need of a non-integratable modulator. In this paper, we combine advantages of both methods by utilizing an integrated electro-absorption modulated laser (EML), in an inverted configuration, as both the master modulation source and the slave laser. Since the EAM and slave laser are integrated on the same chip, the number of discrete components are the same as with a traditional OIL laser system, while exhibiting bandwidths comparable to discrete components.

The experimental setup is shown in Fig. 1. A CW master laser is injected into the EAM side of the EML. The master light is modulated by the EAM and is then injected into the slave laser via the collinear waveguide. Note that the EAM is primarily being used to modulate the injected *master laser light*, not the slave laser light. The slave laser cavity is defined by a DFB grating. A polarization controller is used to align the polarizations of the master and slave lasers. The injection-locked light is then collected from the laser side of the EML and detected via an optical spectrum analyzer (OSA) and a photodetector coupled to a vector network analyzer (VNA).

The laser section of the EML was biased at 30 mA, which corresponds to 3 times the threshold current. The output power from the EAM side was 0 dBm, while the output from the laser side was -3.6 dBm. The EAM is biased at -0.4 V. The DC attenuation from 0 V bias is about -0.9 dB. When the RF modulation is applied to the EAM without injection, the free-running EML modulation response is shown in Fig. 2(a). The 3-dB bandwidth of the EML is ~8 GHz. We then inject 18 dBm from the master laser into the EAM side while continuing to apply the modulation to the EAM. The modulation is detected from the laser-side facet, and the frequency response is shown in Fig. 2, for various detuning frequencies (Δf_{det}). The enhanced resonance frequency of the injection-locked laser is shown in each response. From the negative detuning side (Δf_{det} = -54 GHz) to the positive detuning side (Δf_{det} = -22 GHz), the resonance frequency peak migrates from 32 to 40 GHz, respectively. The free-running EAM response at -0.4 V bias is shown in Fig. 2(a) for comparison. Note that the frequency response is suppressed at the low-frequency end by ~17 dB,

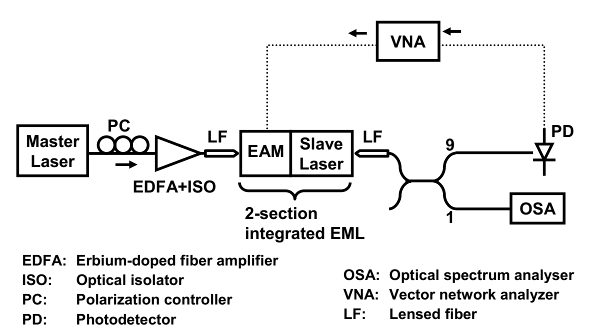

Fig. 1. Experimental setup of MAM-OIL-EML system. Note the integrated EML is the centerpiece of the system. The injected master laser light is optically modulated by the EAM section before being sent to the slave laser. The injection-locked slave laser enhances the EAM modulation and the output is detected from the laser facet side.

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depending on detuning frequency, before leveling off at ~7-8 GHz. This is predicted in the theory [6] and may reduce the effective bandwidth near DC. This technique relies on a good modulation response from the originating EAM. Each frequency response curve in Fig. 2 is simply an enhancement of the original free-running EAM response. Hence, we can isolate the effect of the optical modulation enhancement by subtracting out the free-running EAM response from each injection-locked curve and compensating for the CW power offset due to HR coating on the laser-side facet. This normalized response is shown in Fig. 2(b). It is clear from the smooth responses that the predominant source of the texture of the raw frequency responses is due to the EAM itself; this is removed in the normalized response. Finally, by optimizing the system for broadband performance, we obtain the frequency response in Fig. 3. Here, the EAM bias was slightly reduced and slave laser bias was increased. For the proper detuning value, we can obtain bandwidths of ~45 GHz.

In conclusion, we have demonstrated bandwidth enhancement of EMLs by strong optical injection locking. This technique is very general and will work with any optical modulation device. In this case, the slave laser and modulator are integrated, providing a compact source that is at the level of complexity as an external modulator or simple injection locking system. The system is superior to a optically amplified system due to the possible noise, non-linearity, and chirp reductions of the injection-locked system. Finally, we expect the bandwidth performance to increase with a more superior free-running modulator bandwidth. With commercial modulators available at 40 Gbps, we expect to obtain bandwidths in excess of 100 GHz.

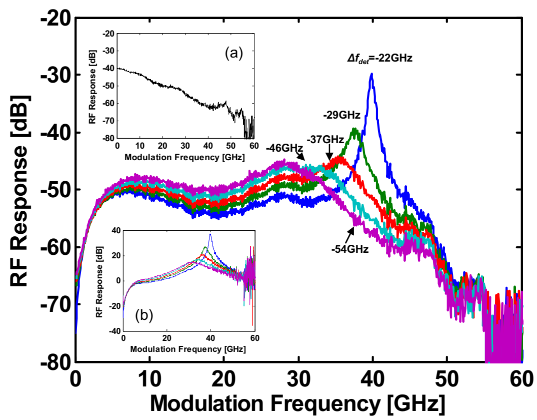

Fig. 2. Frequency response of the injection-locked EML for various detuning frequencies. Inset (a): frequency response of the free-running EML without injection. The higher RF response at low frequencies of the free-running case is due to higher output powers resulting from the HR coated laser facet. Inset (b): Normalized optical modulation response of the injection-locked EML. The raw responses are divided by the free-running EML response and normalized by the DC optical power. Note the low-frequency suppression that occurs for frequencies <6 GHz.

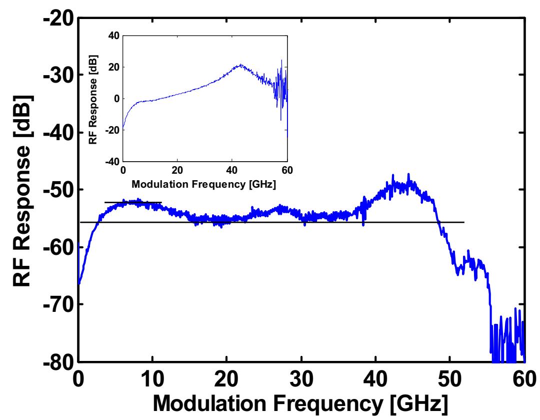

Fig. 3. Frequency response of the OIL-EML when optimized for broadband performance. The EAM was biased at -0.3V, the slave laser current was 40 mA, injected power was 18 dBm, and Δf_{det} = -16 GHz. The plateau at 7 GHz was taken as the 0-dB point. At the high end, the $f_{3\text{-}dB}$ = 48 GHz, while at the low frequency end, the $f_{3\text{-}dB}$ = 3 GHz, giving a total bandwidth of 45 GHz.

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