Hybrid Silicon Mode-Locked Laser with Improved RF Power by Impedance Matching

Bassem Tossoun, Dennis Derickson, Sudharsanan Srinivasan, John Bowers

California Polytechnic State University, Electrical Engineering Department, 1 Grand Avenue, San Luis Obispo, CA 93407 USA
University of California, Santa Barbara, Electrical and Computer Engineering Department, Santa Barbara, CA 93106 USA

ABSTRACT

We design and discuss an impedance matching solution for a hybrid silicon mode-locked laser diode (MLLD) to improve peak optical power coming from the device. In order to develop an impedance matching solution, a thorough measurement and analysis of the MLLD as a function of bias on each of the laser segments was carried out. A passive component impedance matching network was designed at the operating frequency of 20 GHz to optimize RF power delivery to the laser. The hybrid silicon laser was packaged together in a module including the impedance matching circuit. The impedance matching design resulted in a 6 dB (electrical) improvement in the detected modulation spectrum power, as well as approximately a 10 dB phase noise improvement, from the MLLD. Also, looking ahead to possible future work, we discuss a Step Recovery Diode (SRD) driven impulse generator, which wave-shapes the RF drive to achieve efficient injection. This novel technique addresses the time varying impedance of the absorber as the optical pulse passes through it, to provide optimum optical pulse shaping.

Keywords: Silicon Photonics, Mode-Locked, Laser, Optoelectronics

1. INTRODUCTION

The Hybrid Silicon mode-locked laser diode (MLLD) finds a lot of use in applications such as ultra high-speed data processing and sampling, large-capacity optical fiber communications based on optical time-division multiplexing (OTDM) systems. Integrating mode-locked lasers on silicon makes way for highly integrated silicon based photonic communication devices. The mode-locked laser being used in this work was built using the hybrid silicon technology. The work discusses using a passive impedance matching technique at a narrow bandwidth of frequencies, 19.5-20.5 GHz. In the past, impedance matching techniques have been used on mode-locked lasers, such as in 2003, when Arahira and Ogawa achieved a 13 dB improvement of the RF injection efficiency compared with a conventional 50 ohm terminated circuit [1].

The device specifically being used is a ring-cavity mode-locked laser with an emission wavelength of 1570 nm consisting of a 4 mm long ring resonator in silicon coupled to a bus waveguide using an 85/15 multi-mode interference (MMI) coupler. The saturable absorber is 30 µm long and centered in the semiconductor optical amplifier (SOA) section for stable mode locking operation [3]. The MLLD can be biased to passively mode lock at a repetition rate near 20 GHz. A 20 GHz sinusoidal RF generator is also added to actively mode lock the laser in order to reduce timing jitter and to be able to lock the mode locking frequency to other parts of the system.

Silicon Photonics X, edited by Graham T. Reed, Michael R. Watts, Proc. of SPIE Vol. 9367, 93670P · © 2015 SPIE · CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2080117

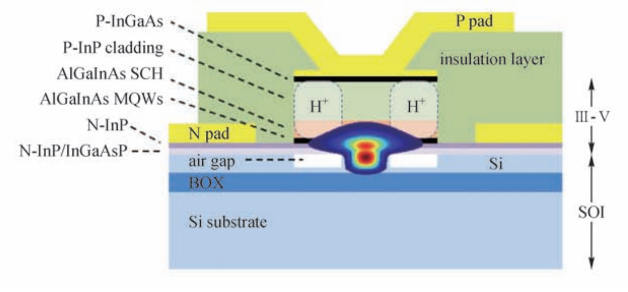

Figure 1: Schematic cross-section of the gain section of the laser identifying the different layers with the optical mode overlaid [2].

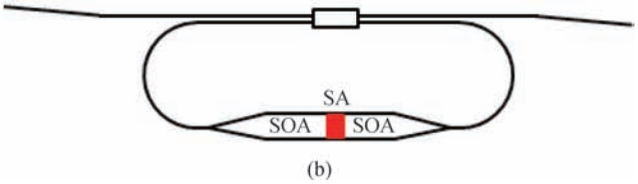

Figure 2: Representation of the gain, absorber and waveguide sections inside the laser cavity. SA is the saturable absorber and the SOAs are the semiconductor optical amplifiers [3], Black lines – silicon waveguides.

2. IMPEDANCE MATCHING NETWORK DESIGN AND RESULTS

2.1 Design and Measurements

In order to efficiently couple energy from the 50 Ω source impedance to the saturable absorber segment, a passive matching network was designed. The load impedance, which is the saturable absorber of the mode-locked laser diode in this case, needs to be known. To achieve a good characterization of the saturable absorber's impedance, a high frequency package was constructed in order to perform accurate scattering parameter measurements on the saturable absorber segment as a function of bias condition. The individual laser diode die was inserted into a package using eutectic die attaching processes for easy connection to power sources and test equipment. First, a copper block was coated with gold, and then indium was used for adhesion of the die to the block. The block is then placed on a heated stage at 195^0C in order to bond the die to the block. Mechanical pressure is applied onto the block in order to support the bonding reaction. Using solder tape or epoxy was another option considered, but there was the possibility of it creeping up on the facet and covering the waveguide. The Indium adhesive material can also creep up of the facet, but it is well controlled by evaporating the material.

Next, a coplanar waveguide was inserted onto the copper block in between the signal source and the laser diode as a transmission line. Generally, in a grounded coplanar waveguide, a conductor is placed on top and bottom of a dielectric. Two slots separate three different sections of the top-placed metal, acting as waveguides for the different transverse electromagnetic (TEM) modes which propagate in the substrate. Figure 3 shows the design of the coplanar waveguide that was used.

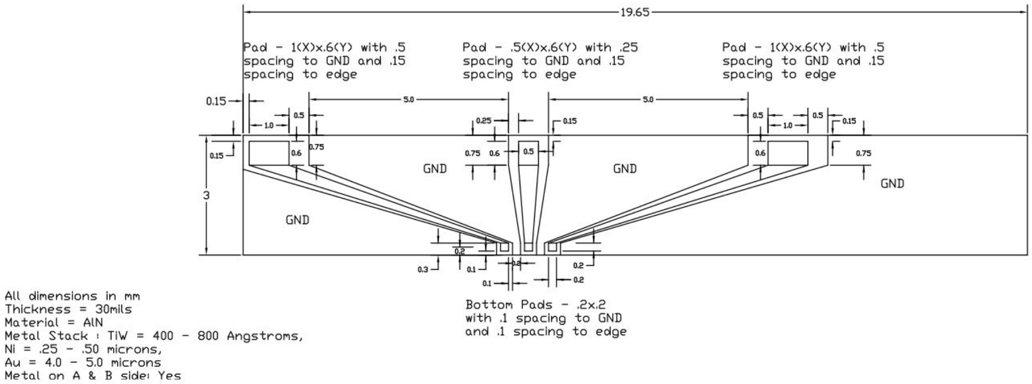

Figure 3: The substrate material used for the coplanar waveguide was Aluminum Nitride. Its dimensions were 19.65 mm x 3 mm x 0.76 mm. ε, the dielectric constant of the ceramic material is 9.14. Titanium-tungsten alloy and nickel were used as adhesion promoters to stick gold on top and on bottom of the ceramic to act as conductors. The waveguides on the Aluminum Nitride ceramic are used as 50Ω transmission lines between the various voltage and current sources connected to the laser diode. The coplanar waveguides on the left and right hand side of the ceramic are used to transmit a DC current bias from a current source to the Semiconductor Optical Amplifiers (SOAs), which act as the gain sections of the laser cavity. The coplanar waveguide in the center is used to transmit power coming from the DC voltage bias and the 20 GHz RF signal to the saturable absorber.

The die containing the mode-locked laser diode (MLLD) is then wire bonded to the coplanar waveguides on the ceramic substrate. Figure 4 shows a process flow diagram of the die and ceramic attaching procedure.

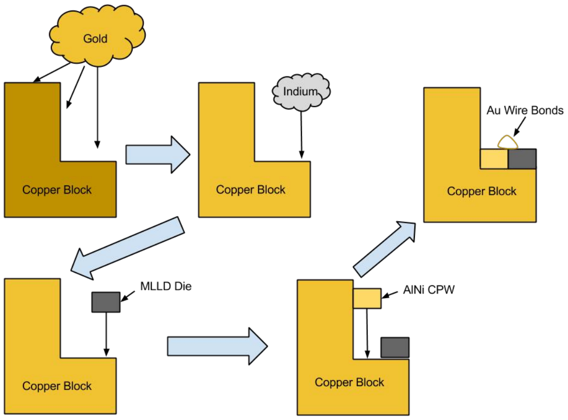

Figure 4: Process flow diagram of die and ceramic attaching processes

A DC bias and an RF signal is applied to the saturable absorber for hybrid mode-locking. The two signals are connected together with a bias tee, which is then transferred onto the center coplanar waveguide. Ground probes are to be placed on top of the ground planes of the waveguide. Figure 5 shows a photo of the complete package.

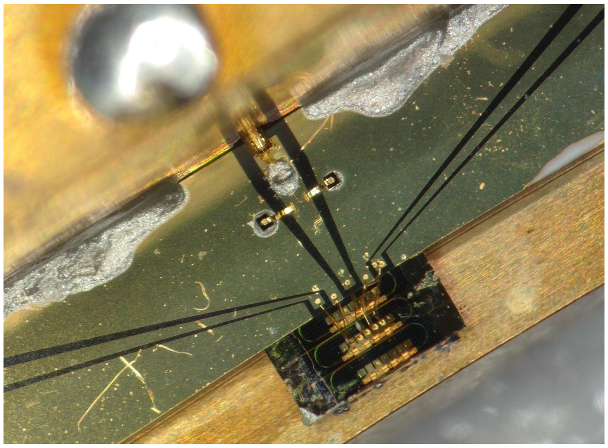

Figure 5: The Completed Packaged MLLD Module

After the diode was completely packaged, a 67 GHz bandwidth Lightwave Component Analyzer was used to measure the device's Scattering (S) parameters. S11 measurements were taken for the laser diode under several bias conditions including when the device is mode-locked. The optical output of the laser was also simultaneously connected to a high speed photodetector and spectrum analyzer to monitor mode-locking modulation performance. A matching network was then designed consisting of two 0.1 pF chip capacitors ribbon bonded to the coplanar waveguide at the designed offset from the laser diode chip. Measurements were then taken for S-parameters of the laser diode under several bias conditions and under a linear frequency sweep from 0 to 40 GHz. Figure 6 provides the final S11 simulation using actual S-parameters for the MLLD and the simulated impedance matching network.`

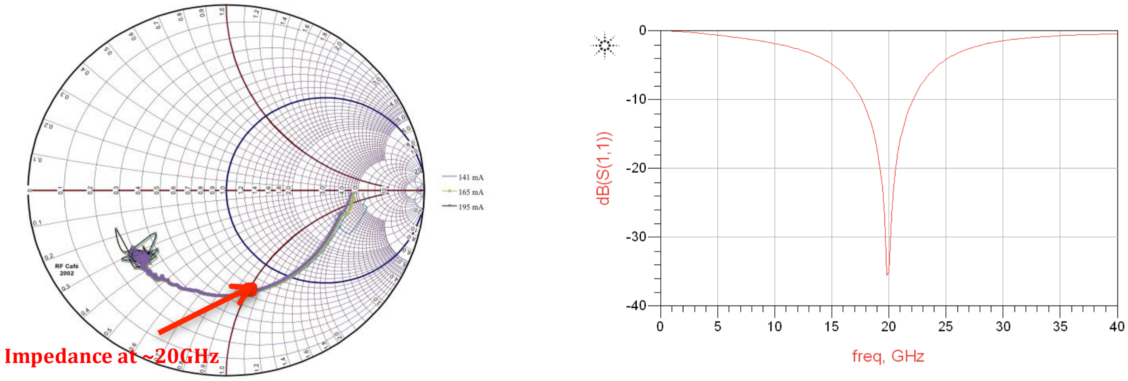

Figure 6: Smith Chart Measurements and Return Loss Simulation for Packaged Diode using measured impedance from the saturable absorber section while operating in a mode-locked laser bias

Although the nonlinear behavior of a laser diode presents a frequency dependent impedance and is dependent upon the current, the impedance of the laser diode used in our case was given as approximately a series resistance of 30 Ohms plus a capacitance of 17 nanoFarads for a frequency range of 19.875 GHz – 20.177 GHz.

Now that there is an accurate measurement of the load impedance, a matching network solution can be made. Using a 50 Ω transmission line, which represents the center conductor of the coplanar waveguide, the load impedance is transformed to one with a positive reactance. Then a 0.2 pF capacitor, wire bonded to the center waveguide, would be used to transform the load impedance to 50 Ω, matching it with the signal generator which injects current into the saturable absorber.

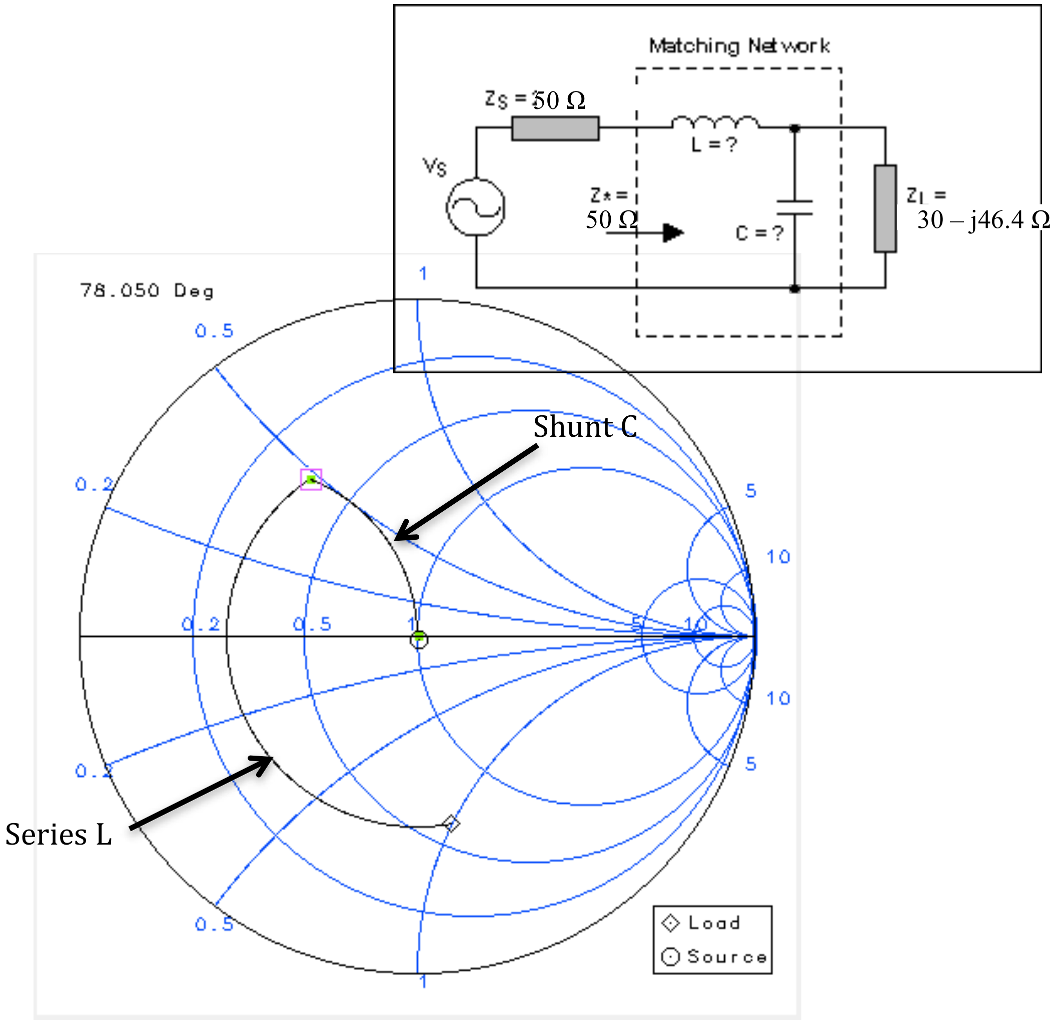

Figure 7: Lumped element Single Open Stub Matching Solution used. Consists of coplanar waveguide acting as a series L, and a capacitor shunted in parallel.

Though, in order to keep equal coupling in both directions of current flow through the waveguide, two capacitors would be inserted on both sides of the waveguide rather than just on one. These capacitors would simply add in parallel, meaning they would both have half the value of the total capacitance. Two capacitors then were used in the matching network designs that follow, each being 0.1 pF, totaling to a equivalent capacitance of 0.2 pF. Also, the interconnect inductance from lengthy wire bonds can cause impedance mismatching and reduced bandwidth [4]. So, the capacitors are instead ribbon bonded to the center waveguide and the ribbon bonds were also made as short as possible to minimize inductance. In Figure 8, a device model of the new matching network is shown, as well as simulation results of S11.

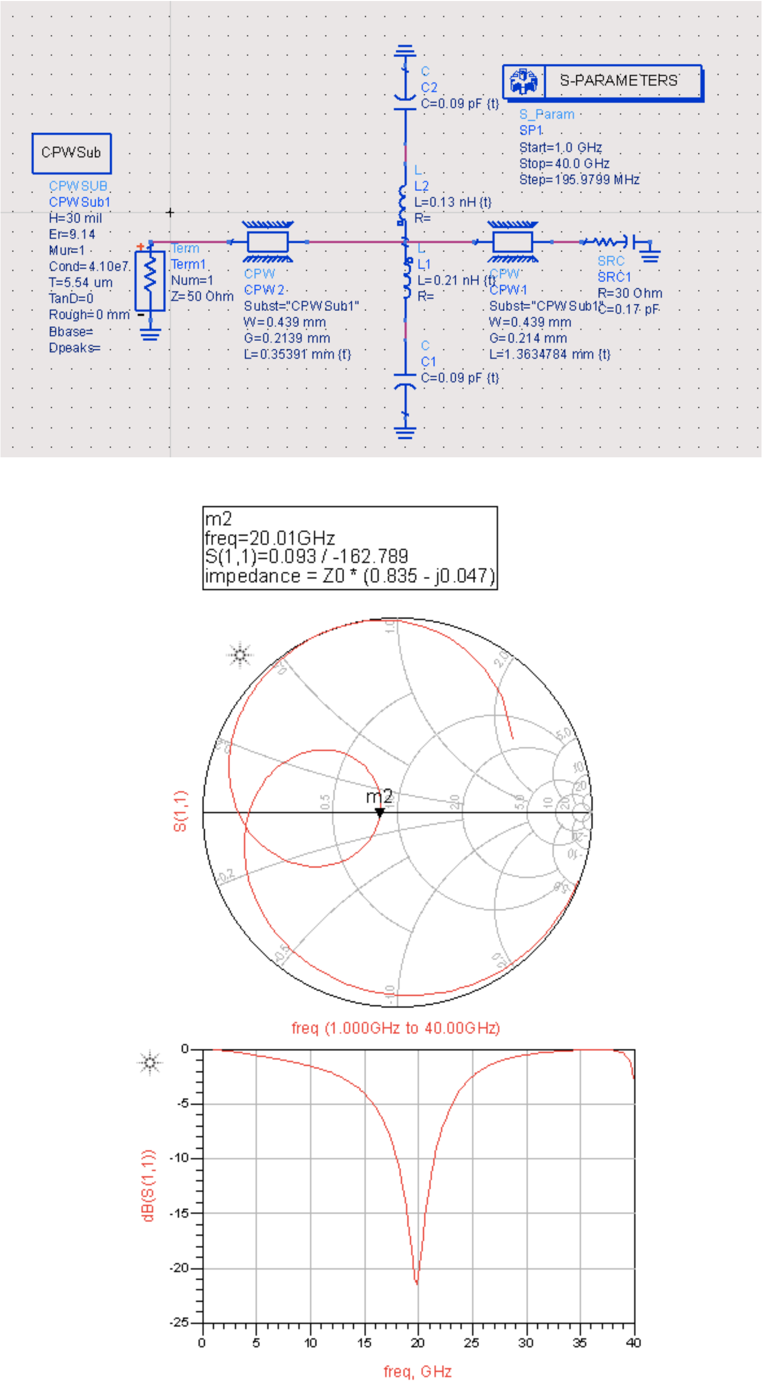

Figure 8: Device Model of matching network with ribbon bonded capacitors and S11 simulation results

Next, in order to measure an improvement in the output power of the MLLD, the optical power coming from the laser is collected using a lensed fiber followed by a high speed photodetector. The saturable absorber was biased at -0.9 V and the SOAs were biased at 191 mA at a steady temperature of 19.8° C, while the RF source signal was at 8 dBm. The laser's RF power is measured using an Electrical Spectrum Analyzer. The setup for this final test is laid out in Figure 9. A direct comparison was made against the case where no impedance matching network was used. Disconnecting the impedance matching network required two ribbon bonds to be removed.

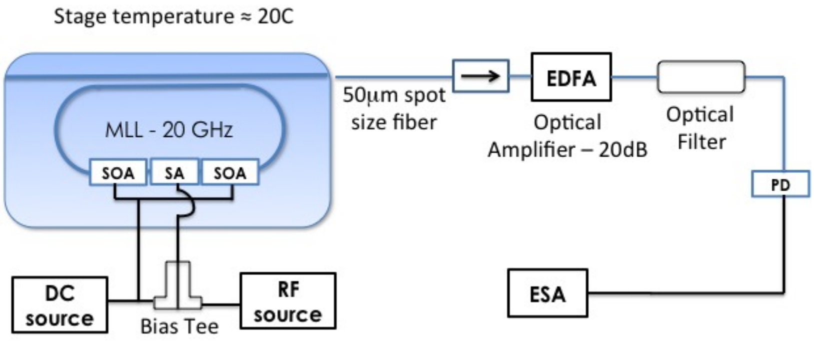

Figure 9: Schematic of the final test setup

A 6 dB increase in RF power coming from the mode-locked laser was observed at the mode-locking frequency when the impedance matching network was inserted onto the module carrying the device. With more RF power being delivered to the laser diode, the diode mode-locks more productively. This means potentially narrower pulse widths, lower phase noise and higher peak powers. If the modulation of the saturable absorber is synchronized more accurately with the round trip time of the optical pulses in the laser cavity, it can reduce the phase noise of the laser, as well as the timing jitter of the pulses from the laser. As a result, the optical pulses become shorter and more intense. With that said, the phase noise of the laser was also improved by about 10dB at a frequency offset of a 100 MHz.

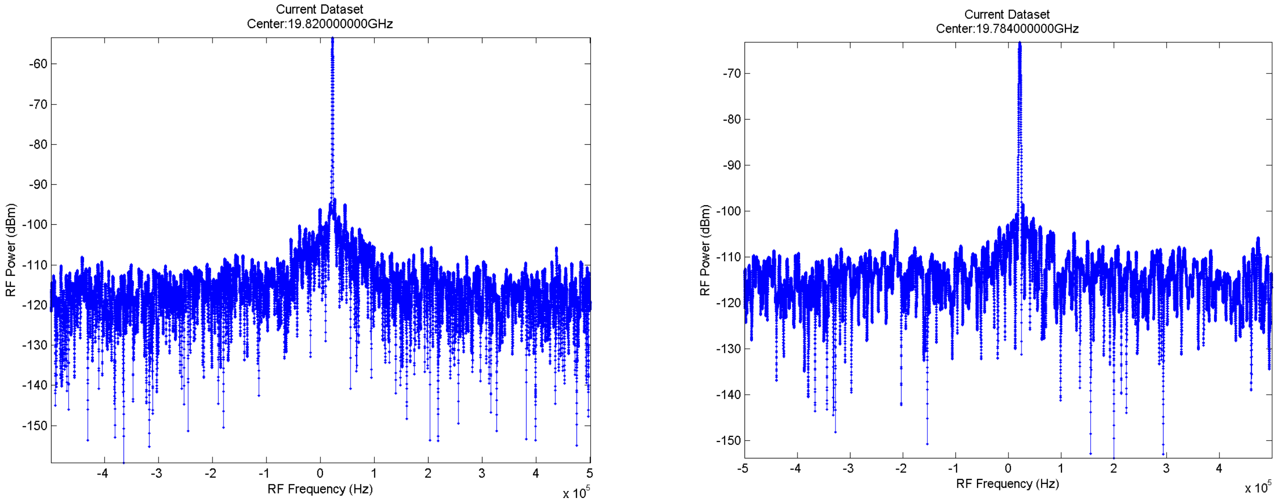

Figure 10: The output of the laser is measured with a high speed photodetector and an electrical spectrum analyzer. The detected spectrum is shown for the MLLD with the impedance matching network connected (left) and without (right) impedance matching network connected. The impedance matched case had a 6 dB higher spectral peak indicating more efficient coupling of the RF driving source to the saturable absorber segment.

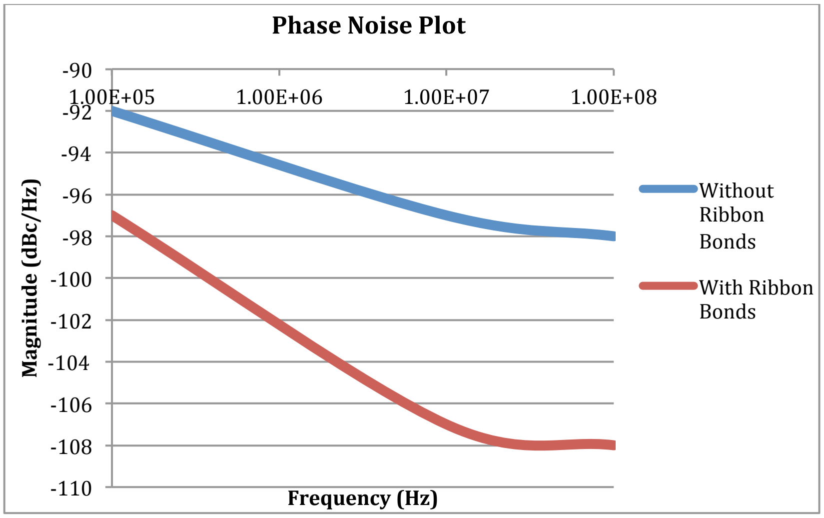

Figure 11: Phase noise for the laser with ribbon bonds attached to coplanar waveguide and ribbons bond not attached to the coplanar waveguide in module.

2.2 Wave-Shaping Active Matching Network

Another idea to consider for efficient RF injection in a mode-locked laser is this idea of an active-matching circuit. The saturable absorber of a mode-locked laser has an impedance that varies with time. When an optical pulse passes through the saturable absorber section, photogenerated carriers are created within the junction of the absorber. Those carriers create an impedance that varies with time, as they are slowly swept out of the absorber section with time. The device structure on the saturable absorber is in essence, a p-i-n diode. The intrinsic region is an undoped zone where no space charges exist and where the quantum wells (QWs) of the absorber are located. The bias voltage applied to the saturable absorber creates a band gap shaping and distribution effect to the quantum wells known as the Quantum Confined Stark Effect (QCSE). [5]

As a result of this, the absorption recovery time increases with increasing reverse bias. In other words, with larger reverse bias, the absorber, can shape the incoming optical pulses better. After the carriers escape the QWs, they are swept to p- and n- contacts. The transit time across the intrinsic region depends on the region's thickness and its reverse bias. For large photocurrent fluctuations the capacitance of the structure, changes due to local reshaping of the band-structure. This actually weakens the QCSE effect, and lengthens absorber recovery time.

With a normal RF sine signal being used, current is injected into the absorber section in order to modulate the absorption of the absorber more accurately to actively mode-lock the hybrid silicon laser. Carriers build up in the saturable absorber as an optical pulse passes through and light is absorbed. One way of solving this problem is to rid of these excess photocarriers as quickly as possible.

In Figure 12 below, an SRD driven impulse generator is shown, which is used to wave-shape the RF drive signal in order to achieve efficient injection. If instead of using a sine signal, a pulse generator were to be used, photocarriers in the absorber QWs may be swept out in time for future incoming pulses. By rapidly applying a large reverse bias right after the optical pulse passes through, unwanted charges are quickly swept out of the absorber's intrinsic region, speeding up absorption recovery time. Now, when the next optical pulse arrives at the absorber, no leftover photocarriers remain from the previous pulse, and the absorber efficiently absorbs the succeeding incoming photons. The simulated output voltage shown in Figure 12.b. is the voltage across the saturable absorber after it is attached to the output of the circuit with an input voltage of 2.5 V. Though, normally the saturable absorber operates in the range of -3V to 2V, so the input voltage would be significantly lower.

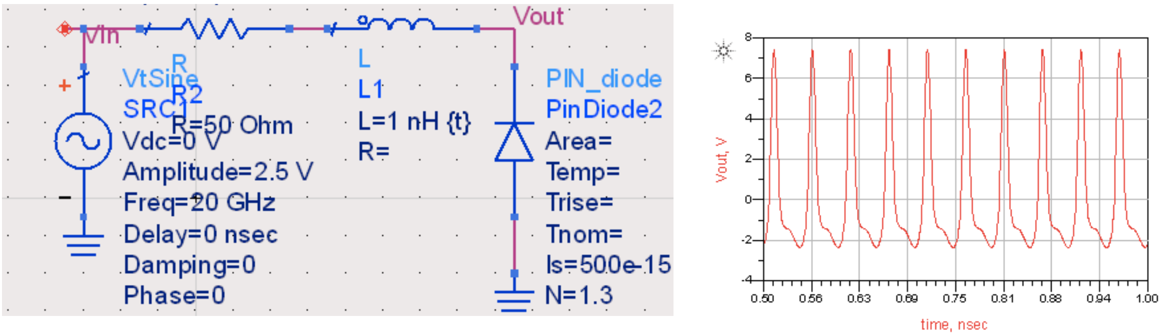

Figure 12: a) The circuit schematic for the SRD driven impulse generator b) The simulated output voltage of the circuit

The circuit developed was an impulse train generator circuit, which converts the input sinusoidal RF signal into a train of impulses with very fast rise times and precisely controlled 180° spacing. Energy is stored into an inductor before a series SRD goes from forward to reverse bias. Then the energy across the inductor causes the step-recovery diode to be driven reverse-biased very fast, getting the charge stored from the forward-biased diode capacitance to be swept out rapidly. This produces voltage spikes from rapid change in current when the diode changes states.

The SRD model used in this circuit was a 12 picosecond transition time SRD made out of AlGaAs materials [6]. The SRD was a p-i-n double heterostructure diode with an ungraded GaAs undoped charge storage region. The zero bias capacitance of the diode was around 156 fF and the minority carrier lifetime was around 0.53 nanoseconds.

In conclusion, this circuit can be considered in the future as an alternative solution to the traditional passive matching network. It is and efficient solution to RF injection efficiency in the saturable absorber of a hybrid silicon mode-locked laser.

SUMMARY

A hybrid silicon mode-locked laser diode was demonstrated with improved coupling of the RF drive signal to the saturable absorber section of the laser. Impedance mismatches between the RF source and the absorber results in some power loss of the RF signal used to actively mode-lock the laser is not optimally applied. Precise scattering parameter measurements along with a robust passive impedance matching network were key elements to improving performance. The impedance matching circuit enhanced the peak optical power coming from the laser while mode-locking, and produced a 6 dB (electrical) increase in the modulation power, as well as approximately a 10 dB phase noise improvement, which had been measured in an electrical spectrum analyzer. Also, we provide suggestions for future work. One area of future work is to provide optimized electrical pulse shaping waveforms for the RF drive source instead of sinusoidal drive waveforms in order to improve injection efficiency when the laser is actively mode-locked.

REFERENCES

[1] Arahira, S., Ogawa, Y., “40 GHz Actively Mode-Locked Distributed Bragg Reflector Laser Diode Module with an Impedance-Matching Circuit for Efficient RF Signal Injection”, Japanese Journal of Applied Physics, Vol. 43, No. 4B, pp. 1960–1964, 2004

[2] Bowers, J., Liang, D., Fang A., Park H., Jones R., Paniccia M., “Hybrid Silicon Lasers: The Final Frontier to Integrated Computing” in OPN Optics & Photonics News, Massachussetts Ave, NW, 2010

[3] Srinivasan, S., Davenport, M., J.R. Heck, M., Hutchinson, J., Norberg, E., Fish, G., Bowers, J., “Low phase noise hybrid silicon mode-locked lasers” in Frontier Optoelectronics, Beijing, China, 2014

[4] Natel Engineering, “Wire Bond vs. Ribbon Bond,” Natel Engineering [Online]. Available: http://www.natelems.com/documents/dg6RBvsWB.pdf.

[5] Isomaki, A. “Ultrafast Fiber Lasers Using Novel Semiconductor Saturable Absorbers and Photonic-Crystal Dispersion Compensators”, Tampere University of Technology, Publication 682, October 2007.

[6] Hewlett-Packard, Appl. Note 918, pp.7-9