# Monolithic Linewidth Narrowing of a Tunable SG-DBR Laser

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**Abstract:** We demonstrate an InGaAsP/InP widely-tunable SG-DBR laser integrated with an asymmetric Mach-Zehnder interferometer (AMZI) for frequency stabilization. Negative feedback from the AMZI to the laser phase tuning section reduces the linewidth by a factor of 27.
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## 1. Introduction

Tunable lasers have become increasingly important for a variety of applications, such as optical sensing and coherent detection. They can allow large cost savings by increasing flexibility and decreasing inventory demands in dense wavelength division multiplexing, compared to using many types of lasers with different wavelengths [1]. Many of these applications will be greatly aided by a low linewidth compact laser. As coherent detection moves to higher modulation formats, lower phase noise will be required of the local oscillator [2-4]. High resolution optical sensing, such as FMCW LIDAR, also requires a low phase noise laser for longer range detection.

Many different methods have been developed to reduce the linewidth of tunable lasers. Several extended cavity lasers with linewidths well below 100 kHz have been demonstrated [5,6]. Tunable DFB laser arrays have shown less than 160 kHz linewidth through optimization of the cavity [7]. The Pound-Drever-Hall technique can reduce linewidth to the sub 100 Hz level [8]. However, most optical methods of decreasing linewidth increase the laser size and are very sensitive to environmental fluctuations. Alternatively, tunable DFB arrays have high performance, but require many DFB lasers integrated on one chip to enable a large tuning range.

Much research has focused on negative electrical feedback using the error signal from a frequency discriminator to tune the laser and reduce the linewidth. This technique has the potential to be more stable and maintain a small cavity size. It has been successfully implemented using many different filters as the frequency discriminator, such as a Fabry-Pérot etalon, a fiber Mach–Zehnder and a fiber Bragg grating [9-12]. Advantages of this method include its simplicity and low cost. However, previous implementations have been bulky and increased the size of the laser package.

In this paper, we have demonstrated for the first time linewidth reduction through the use of an asymmetric Mach–Zehnder interferometer (AMZI) frequency discriminator that has been monolithically integrated in a photonic integrated circuit (PIC) with a 40nm tunable SG-DBR laser diode and waveguide detectors. When using an AMZI as a frequency discriminator, the quadrature point of the AMZI is used to convert the frequency error of the laser to amplitude error. This error is then fed back to the phase tuning section of the laser through a stabilizing loop filter, suppressing the frequency noise within the loop bandwidth of the negative feedback loop. The path length imbalance in the AMZI is 1.5 mm, leading to a free spectral range of 60 GHz. Integration has allowed us to keep the advantages of size, weight and power inherent in semiconductor lasers and simultaneously attain low linewidth. Due to the small chip size, the feedback loop delay is kept small, facilitating a loop bandwidth upwards of 250 MHz and linewidth reduction by a factor of 27.

## 2. Design and Fabrication

An SG-DBR laser, AMZI, semiconductor optical amplifiers (SOAs), compact 2x2 multimode interferometer couplers and waveguide detectors are integrated on an InGaAsP/InP centered quantum well platform consisting of 10/11 6.5 nm/8 nm InGaAsP QWs/barriers centered within a 105 nm upper and lower 1.3Q InGaAsP waveguide. Surface ridge (SR) waveguides are used for the SG-DBR laser for improved thermal characteristics and lower loss. Deep ridge (DR) waveguides have a higher confinement, thus smaller bending radius and are therefore used for the AMZI, so that a 1.5 mm path length difference can be achieved within a smaller device footprint. A waveguide transition element is used between the two waveguide topologies. A schematic of the epitaxial structure and SEMs of the device in various stages of fabrication are shown in Fig. 1.

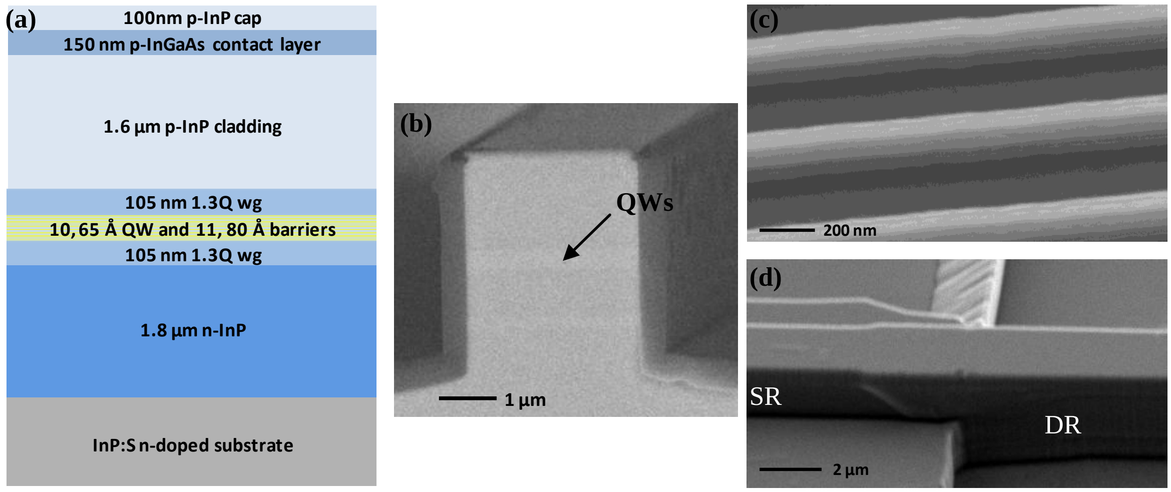


Fig. 1. a) Schematic of epitaxial structure after regrowth, and scanning electron micrograph (SEM) of b) cleaved deeply etched ridge facet, c) SG-DBR gratings pre-regrowth and d) surface ridge to deep ridge waveguide transition.

Quantum well intermixing is used to define the passive regions [13], and gratings are defined via electron beam lithography and dry etched using a $CH_4/H_2/Ar$ based RIE etch. Blanket regrowth of the p-InP cladding, p-InGaAs contact layer and p-InP protective cap layer is done using metalorganic chemical vapor deposition. The SR and DR waveguides are defined using a bilayer Cr and $SiO_2$ hardmask. The Cr is etched using a low power $Cl_2/O_2$ ICP RIE etch and the $SiO_2$ is etched using a $SF_6/Ar$ ICP RIE etch. An initial shallow dry etch of both waveguides is performed using a $Cl_2/H_2/Ar$ 200°C 1.5 mT ICP RIE Etch [14], defining the waveguide everywhere. Then, the DR waveguide is protected and the SR waveguide is completed via a HCl based crystallo-graphic wet etch. Next, deposition and liftoff of $SiO_2$ is used to protect the SR regions and the DR waveguide is deeply etched using the $Cl_2/H_2/Ar$ etch mentioned above. An isolation layer of $Si_3N_4$ is then deposited, vias are opened using a semi-self alignment process for the top p-contacts, and Pt/Ti/Pt/Au p-contacts are evaporated via e-beam deposition. The sample is then thinned to 140 µm, Ti/Au backside metallization is deposited for the n-contacts, and output facets are formed via cleaving.

## 3. Linewidth Narrowing

The PIC, an electronic integrated circuit (EIC) and loop filter are mounted on AlN carriers and wirebonded together. The EIC consists of a differential limiting amplifier that allows use of both detectors on the PIC in a balanced detector configuration to decrease intensity variation, and provides a -2V bias to the detectors on the PIC. The loop filter is a second order frequency lock loop made of discrete resistors, capacitors and op-amplifiers that provides gain and the correct loop characteristics for stable frequency locking. A feed forward path is utilized to minimize loop delay at high frequencies and increase the loop bandwidth [15]. Schematics of the frequency response of the frequency discriminator and device set up are shown in Fig. 2.

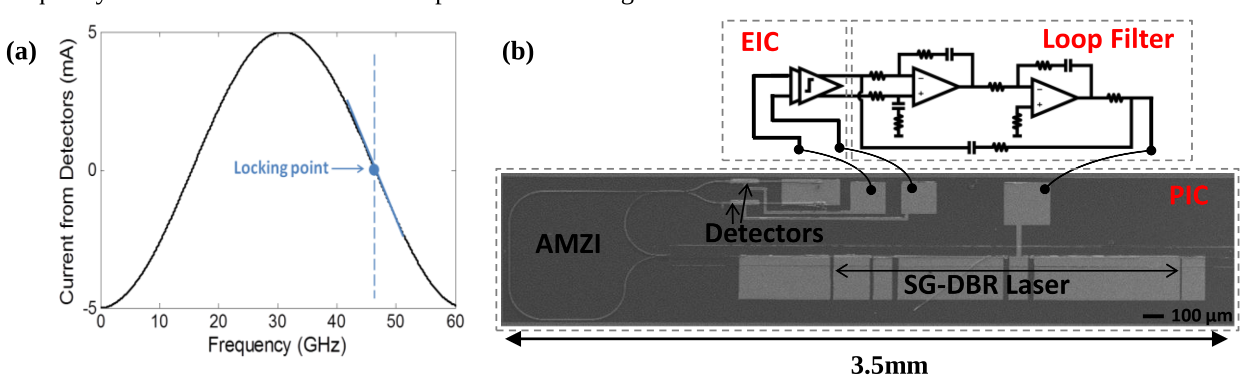


Fig. 2. a) Calculated detector current vs. operating frequency and b) SEM of the fabricated PIC along with a depiction of the connections to the EIC and loop filter.

Self-heterodyne was used to measure the 3-dB linewidth of the SG-DBR laser. The output of the SG-DBR was split using a 1x2 fiber coupler, one arm was delayed by 25 km, the other arm went through a 100 MHz acousto-optic modulator, and the arms were recombined. The signal was then detected by an external detector and monitored on an electrical spectrum analyzer (ESA).

The 3-dB linewidth of the SG-DBR laser prior to locking was 80 MHz, which was mainly dominated by large 1/f noise at low frequencies. After locking the linewidth was 3 MHz, showing a 27x improvement in linewidth. The linewidth spectrums have been overlaid and are shown in Fig. 3. The loop bandwidth was larger than 250 MHz.

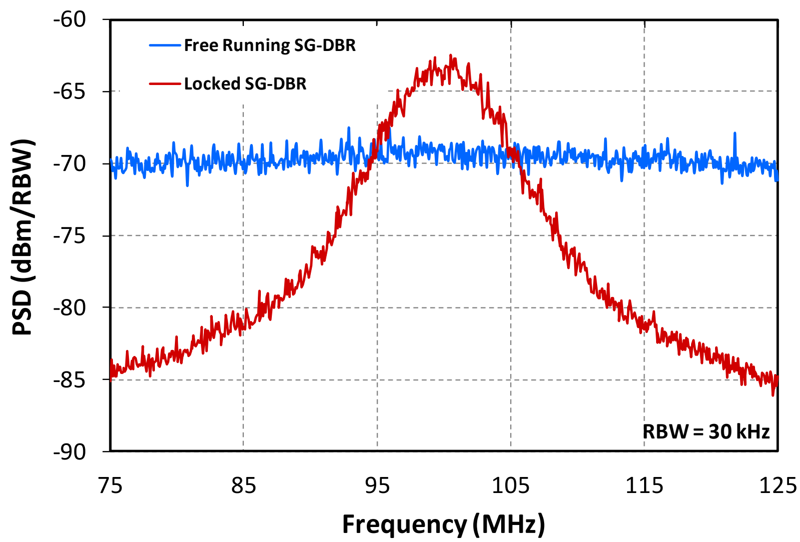


Fig. 3. Self-heterodyne linewidth spectrum of the free running SG-DBR laser and frequency locked SG-DBR laser taken from an ESA.

## 4. Conclusion

Self referencing was used to frequency lock an SG-DBR laser to an AMZI integrated within the same chip and a 27x linewidth improvement was demonstrated. Locking was extremely robust and was maintained over several hours with no environmental isolation. This technique shows promise for achieving a low-linewidth widely tunable laser with all the size, weight and power advantages of a photonic integrated circuit. Future optimization of the feedback loop gain and the test setup is anticipated to yield additional linewidth improvement.

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