A High efficiency, Current Injection Based Quantum-Well Phase Modulator Monolithically Integrated with a Tunable Laser for Coherent Systems

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Abstract: A monolithically integrated tunable laser and quantum-well phase modulator is demonstrated. Phase efficiency under forward bias is improved >20dB at low frequencies compared with reverse bias. Bandwidths >30 GHz are demonstrated in frequency modulation measurements.

OCIS codes: (230 4110) Modulators; (230 5590) Quantum Well Devices

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1. Introduction

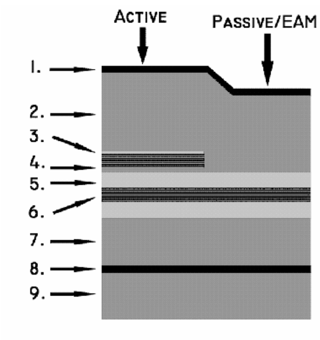
Optical phase modulation continues to attract increased interest in optical communications systems. In digital systems, phase modulation offers increased receiver sensitivity, improved tolerance to fiber dispersion effects and constant envelope, which are attractive for WDM optically amplified links. Optical phase modulation is also well-positioned to generate very linear analog optical links. Linear optical intensity modulators have been difficult to realize because of the requirement to force a linear transfer function between the two hard limits of zero and full optical transmission. Optical phase modulation, meanwhile, does not have these limits. A linear phase modulator can be engineered by increasing the available output phase swing while keeping the modulation within the linear regime of the transfer function, in a manner that parallels the linearity of microwave amplifiers.

Semiconductor phase modulators based on the InGaAsP/InP materials system are particularly attractive since they can be integrated with other discrete components such as lasers for low packaging costs and coupling losses. For phase modulation these devices employ a variety of mechanisms including current injection based effects, such as the free carrier plasma effect, and field based effects such as the quantum confined stark effect (QCSE). Devices based on current injection in quantum wells are particularly attractive due to their large achievable change in refractive index. However, integrating quantum well based phase modulators with lasers has required advanced growth techniques [1], and results have been limited to single frequency DFBs. In this work, we demonstrate the first monolithically integrated sampled grating DBR laser tunable transmitter/phase modulator with index shifts up to $\Delta n = 0.019$ by applying current injection into quantum wells. Compared to current injection into a bulk waveguide, quantum wells have been shown to provide superior phase modulation efficiency [2]. The device is fabricated on a modified offset quantum well platform and requires only a single blanket InP regrowth step [3]. We observe improvements up to 20 dB for phase modulation efficiency at low frequency for current injection conditions compared with reverse bias conditions employing the QCSE

To overcome the sinusoidal response of a standard optical phase demodulator, we have proposed the use of an optical phase-lock loop (OPLL) to form a linear phase demodulator [4]. In its electrical counterpart, a voltage controlled oscillator is normally used to track the incoming phase with zero steady state error. A frequency modulated laser can take this function, in essence being a current controlled oscillator (CCO). However, in practice, a laser CCO will not simultaneously meet the twin requirements of high modulation bandwidth and low laser phase noise of the most high-performance optical phase-lock loops. It has previously been shown that a phase modulator operating beyond its traditional 3-dB bandwidth produces frequency modulation [5]. Along with the demonstration of a tunable phase modulator transmitter, we also show for the first time that the current injection based quantum well phase modulators can generate frequency modulation with a response up to 35 GHz, and that these devices are suitable for integration as a CCO in an optical phase-lock loop.

2. Epitaxial Structure and device layout

The phase modulator is fabricated as part of an integrated Mach-Zehnder interferometer in combination with a tunable sampled grating DBR (SGDBR) laser source using a modified offset quantum well based integration platform [3]. The mach-zehnder design was selected for ease of characterization, since in this configuration, changes in phase are translated into an amplitude response which can be easily measured using an optical power meter. A diagram of the epitaxial layers for device fabrication is shown in Fig. 1.



Region	Description
1	p-contact
2	p-cladding
3	Offset QWs
4	Stop Etch
5	Waveguide
6	Centered QWs
7	n-Buffer
8	n-contact
9	Fe-substrate

Fig 1. Epitaxial layer structure for the modified offset quantum well phase modulator/SGDBR integration platform

Laser and propagation/phase modulator regions are separated by the selective removal of the offset quantum well stack that is used for gain in the optical amplifiers and the laser. A simple,blanket p-type InP regrowth follows the selective removal of the offset wells, after which exposed waveguides are patterned and etched. Phase modulator regions are formed by evaporating a Ti/Pt/Au contact on the top of the exposed ridges and electrically isolating devices using a proton implant. In the center of the waveguide, a quantum well superlattice is designed to have a photoluminescence of 1460 nm and consists of 8x10 nm compressively strained wells and 7x5 nm tensile strained barriers. The optical waveguide regions surrounding the wells have a photoluminescence peak at 1350 nm. Integrated devices were thinned, cleaved, anti-reflection coated, mounted on AlN carriers, and wirebonded.

3. Results

The refractive index shifts, along with 50 Ω terminated small signal frequency response curves were generated for the integrated Mach-Zehnder/SGDBR laser transmitter. The index shift was measured by monitoring the DC extinction characteristics of the Mach-Zehnder when a 300 um long electrode in one of the arms is forward biased and the laser wavelength is tuned to 1550 nm. Results are shown in Fig. 2 and Fig. 3.

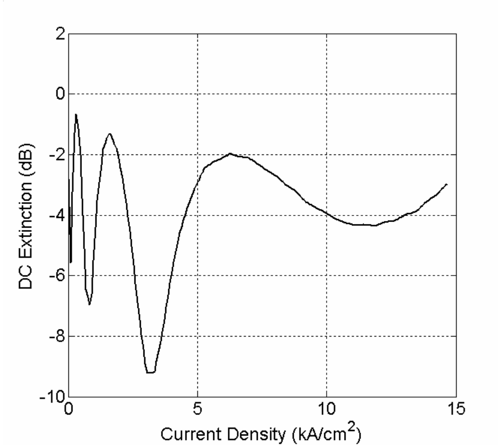


Fig 2. DC Extinction characteristics of integrated tunable SGDBR laser and Mach-Zehnder modulator at 1550 nm.

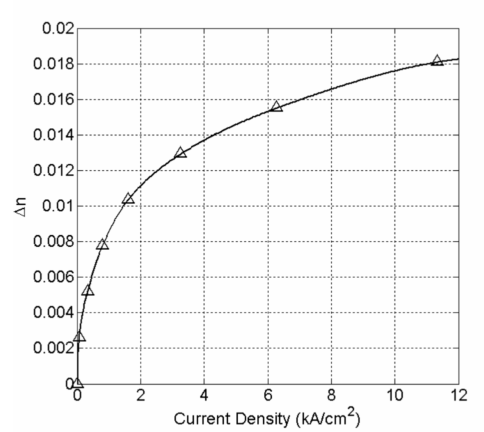


Fig 3. Experimental index shift for current injection based phase modulator. A trend line has been added to guide the eye.

In the frequency response measurements, the forward or reverse DC bias conditions are set through a bias-T that is linked to a current/voltage source. The small signal is applied through a 50 Ω terminated ground signal probe.

Under forward bias operation, the DC bias point is set to 10 mA. Under reverse bias, the applied voltage is -2V. Results are shown in Fig. 4.

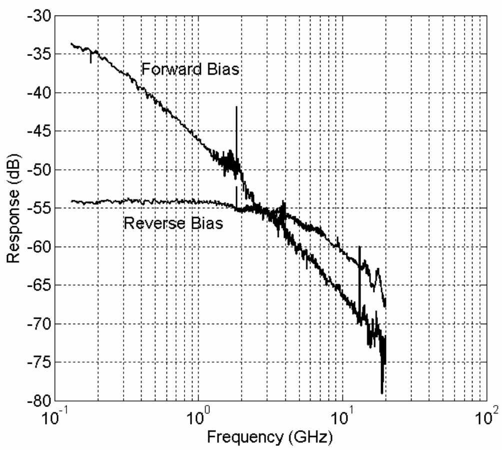


Fig 4. Small signal amplitude response for the Mach Zehnder under forward and reverse bias conditions.

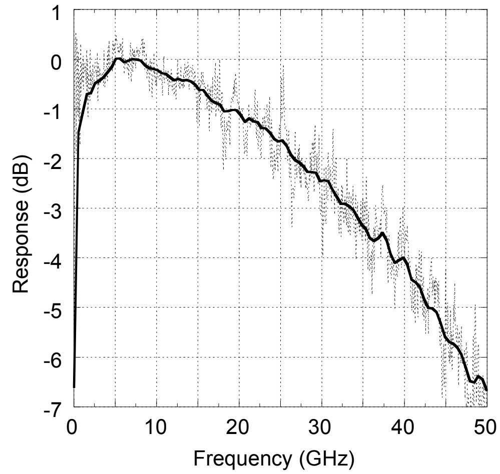


Fig 5. Small signal response of the CCO phase modulator with optical frequency discriminator

The un-normalized frequency response measurements of these devices show up to 20 dB improvement in phase efficiency using current injection at low frequencies when compared with the reverse bias quantum confined stark effect approach. It should be noted that under forward bias conditions, the RF matching is poor due to the small device impedance (~10 Ω) and improving this would lead to even greater efficiency.

Finally, we have used this device under forward bias conditions in combination with an optical filter for frequency discrimination as in [1], and measured the resulting FM response. This is of great relevance for applications in an optical phase-lock loop, where any roll-off in the FM frequency response will add a loop phase lag, reducing the stability of the phase-lock loop. For a phase modulator with a pure 1/f-type phase response, we would expect that the corresponding FM response is flat. This is also what we observe in the experimental results that are shown in Fig. 5. Greater than 35 GHz bandwidth is obtained, which makes this device an excellent candidate for optical phase-lock loop applications with loop bandwidths up to and exceeding 10 GHz.

4. Conclusions

We have demonstrated a monolithically integrated quantum well phase modulator in a Mach-Zehnder configuration with a widely tunable Sampled Grating DBR laser. The phase efficiency under both forward and reverse bias conditions has been investigated and we have shown up to 20 dB improvement in phase response for forward biased current injection conditions at low frequency. We have also used this device to generate optical frequency modulation and observe a 3-dB bandwidth in excess of 35 GHz.

5. References

[1] T. Tanbun-Ek, P.F. Sciortino, Jr, A.M. Sergent, K.W. Wecht, P. Wisk, Y.K. Chen, C. G. Bethea, S.K. Sputz, "DFB Lasers Intergated with Mach-Zehnder Optical Modulator Fabricated by Selective Area Growth MOVPE Technique" IEEE Photon. Tech. Lett., vol. 7, no. 9, pp. 1019-1021, 1995.

[2] J.I Shim, M. Yamaguchi, P. Delansay, M. Kitamaru, "Refractive Index and Loss Changes Produced by Current Injection in InGaAs(P)-InGaAsP Multiple Quantum –Well (MQW) Waveguides" IEEE J. Select. Topics in Quantum Electron., vol. 1, no. 2, pp. 408-414, June 1995.

[3] M.N Sysak, J.S. Barton, J.W. Raring, M. Dummer, A. Tauke-Pedretti, D.J. Blumenthal and L.A. Coldren. "10 Gb/s Photocurrent Driven, Widely Tunable Electroabsorption Based Wavelength Converter*" presented at Optical Fiber Communications Conference,* Anaheim, CA 2005. OtuM4

[4] Hsu-Feng Chou, A. Ramaswamy, D. Zibar, L.A. Johansson, J.E. Bowers, M. Rodwell and L..A. Coldren, "SFDR Improvement of a Coherent Receiver Using Feedback," Submitted to COTA 2006.

[5] L.A. Johansson, J.S. Barton, L.A. Coldren. And G.A. Fish, "High-Speed Optical Frequency Modulation in a Monolithically Integrated Widely-Tunable Laser - Phase Modulator," in *Optical Fiber Communication Conference on CD-ROM (Optical Society of America, Washington, DC, 2004),* FL2