40 Gbps Series-Push-Pull Mach-Zehnder Transmitter on a Dual-Quantum-Well Integration Platform

Anna Tauke-Pedretti, *Student Member, IEEE,* Matthew N. Sysak, *Member, IEEE,*
Jonathon S. Barton, *Member, IEEE,* Leif Johansson, *Member, IEEE,* James W. Raring, *Student Member, IEEE,*
and Larry A. Coldren, *Fellow, IEEE,*

***Abstract*— A series-push-pull Mach-Zehnder modulator is integrated with a sampled-grating DBR laser on a dual-quantum-well integration platform. The device exhibited greater then 7.8 dB extinction at 40 Gbps with a 2.5 V drive voltage across a wavelength range of 1541 nm to 1566 nm. Bit Error Rate (BER) measurements at 10 Gbps showed error free operation and negative chirp.**

***Index Terms*— tunable lasers, optical modulation, photonic integrated circuits (PICs), optical transmitters, Mach-Zehnder modulator, semiconductor optical amplifier (SOA), sampled-grating DBR laser (SGDBR), offset quantum wells.**

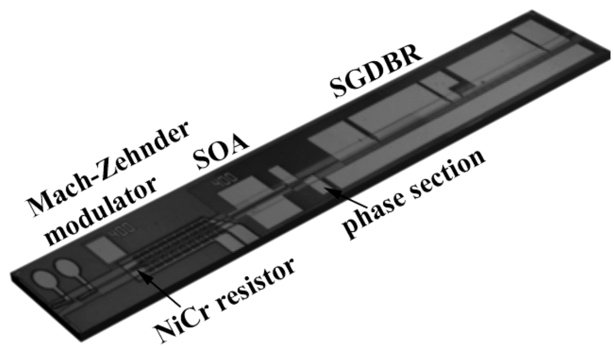

Fig. 1. Diagram of integrated widely tunable transmitter chip

I. INTRODUCTION

INCREASED data volumes in next generation networks are requiring transmission systems to embrace 40 Gbit/s data rates. Such systems require transmitters with low drive voltages for minimal power consumption, high bandwidths to accommodate increased bit rates, and tailorable chirp to counteract dispersion. While some of these needs can be addressed with electroabsorption modulator (EAM) based transmitters, it has been difficult to demonstrate an EAM-based solution with tunable chirp. As a more viable alternative, Mach-Zehnder modulator based transmitters are well positioned to manage the detrimental dispersion effects at these high bit rate [1].

Previously, several 40 Gbps transmitters have been reported; these devices include discrete high-speed InP-based Mach-Zehnder modulators [1],[2] and monolithically integrated transmitters [3]. Of particular interest is a small footprint, high-speed Mach-Zehnder modulator integrated with a widely tunable laser similar to [3] that uses quantum-wells within the waveguide for highly efficient index modulation and low capacitance [4]. These broadband transmitters reduce packaging costs, decrease coupling losses and reduce network provider inventory requirements.

This paper presents a 40 Gbps widely tunable Mach-Zehnder transmitter fabricated on a Dual-Quantum-Well (DQW) integration platform. This device implements a widely tunable sampled-grating DBR (SGDBR) laser, two parallel semiconductor optical amplifiers (SOAs) within the interferometer and a series-push-pull Mach-Zehnder modulator with an integrated termination resistor.

This work was supported by Defense Advanced Research Projects Agency (DARPA) MTO-LASOR Grant W911NF-04-9-0001 and MTO-CS-WDM Grant N66001-02-C-8026.

Authors are with the Department of Electrical and Computer Engineering and the Department of Materials, University of California Santa Barbara, Santa Barbara, CA 93106 USA (telephone: 805-893-5955, email: atauke@engineering.ucsb.edu).

II. DEVICE AND INTEGRATION PLATFORM

A schematic of the widely tunable Mach-Zehnder transmitter is shown in Fig. 1. The SGDBR laser consists of five sections - an active absorber, a rear mirror, a phase section, a 500 μm long gain section, and a front mirror. This is followed by a Mach-Zehnder interferometer with a 400 μm SOA in each arm to increase the output power of the device and compensate for propagation losses. Phase sections within the interferometer arms are forward biased to achieve π-phase-shift. A flared and curved output waveguide, as well as an AR coating was used to reduce optical reflections and to aid in fiber coupling.

The 400 μm long Mach-Zehnder is operated in a series-push-pull fashion with the RF signal applied across the modulator electrode (Fig. 2). This configuration allows for small chirp values and high bandwidth due to the series connection of the two Mach-Zehnder arms. The modulator has a traveling wave electrode segmented into 8-50 μm long T-sections to capacitively load the transmission line allowing for better impedance matching to 50 Ω [3], [6]. The ridge width is reduced from 3 μm in the laser and SOA regions to 2 μm within the modulators. In addition to the thinner ridge widths, photo-bis-benzocyclobutene (BCB) is used underneath the modulator electrode to reduce the parasitic capacitance. An integrated 50 Ω NiCr load resistor provides on chip termination, thus reducing RF losses.

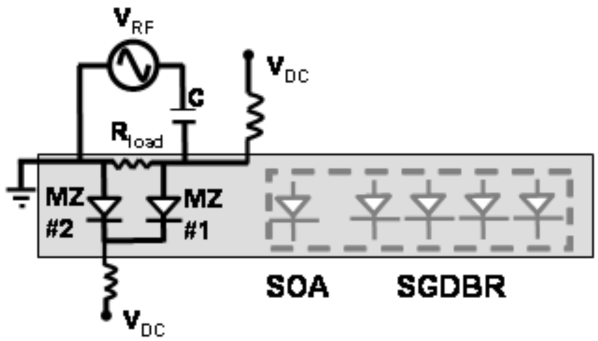

Fig. 2. Schematic of series-push-pull biasing scheme

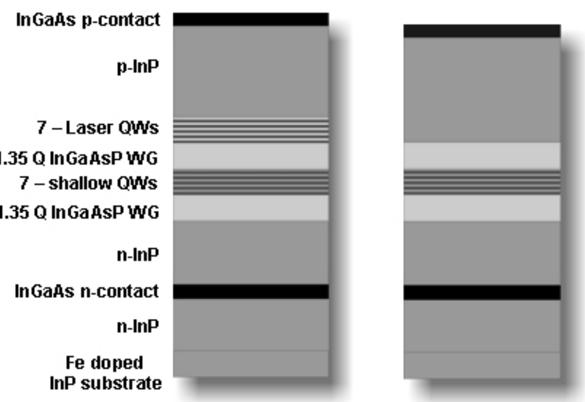

Fig. 3. Schematic of the dual-quantum-well integration platform. The SOA and laser gain regions with the offset-quantum-wells are on the left. Passive and modulation regions with the offset wells removed is shown on the right.

The fabrication of this device requires a single blanket regrowth of the InP cladding and InGaAs contact layer following the selective removal of the set offset quantum-wells from the passive sections and the etching of holographically defined sampled gratings.

The transmitter's MOCVD grown epitaxial structure (Fig. 3) is based on the dual-quantum-well integration platform [5]. In this approach a set of offset quantum-wells (photoluminescence = 1550 nm) located above the waveguide layer are used for the gain section of the SGDBR and the SOAs. A separate set of quantum-wells (photoluminescence = 1480 nm) are centered in the InGaAsP waveguide layer to aid the modulator efficiency. The implementation of the DQW integration platform provides a reduction in capacitance and thus an increase in bandwidth compared to bulk waveguide devices. This is due to the lower waveguide doping requirement in the DQW devices which increases the p-n junction depletion region.

III. Experiments

Following fabrication, the devices were thinned, cleaved and mounted onto an aluminum nitride carrier for testing. All DC contacts were wirebonded to the carrier and contacted via a probe card. The modulator was directly probed with a ground-signal RF probe to prevent any parasitic effects from wirebonds.

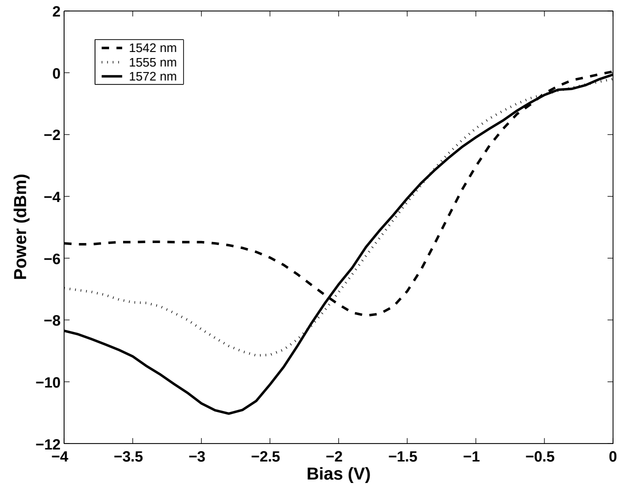

Fig. 4. DC extinction vs. voltage for single-sided 400 μm-long devices. ($P_{out} \simeq 1$ mW)

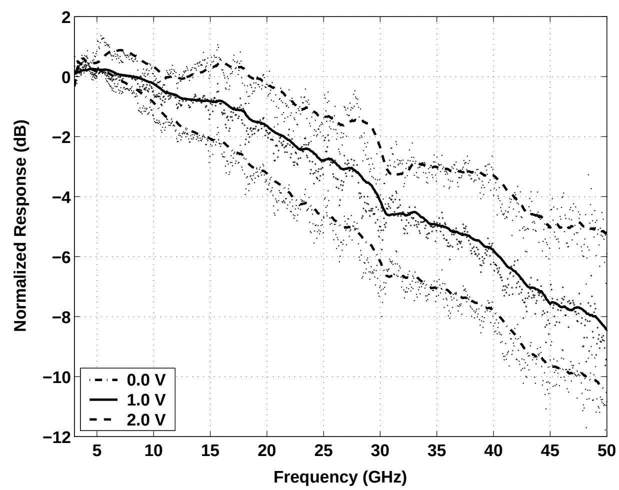

Fig. 5. Bandwidth of transmitter of different Mach-Zehnder reverse biases. (I_{gain} = 130 mA; I_{SOA1} = I_{SOA2} = 100 mA; I_{phase} = 9.575 mA)

Single-sided DC extinction for the 400 μm-long device was measured with one electrode held at a constant 0 V bias while the bias voltage across the other electrode was varied between -4 V to 0 V. As shown in Fig. 4, the wavelength dependance of the device shows a V_π variation of $\sim$1 V across the wavelength range. The maximum DC extinction value increases with longer wavelengths where there is less absorption so there is a better optical power balance between the Mach-Zehnder arms. This power differential is not an issue when the device is operated in a series-push-pull fashion, since both arms have an identical DC reverse bias and the absorption is similar.

Bandwidth measurements have been taken for various modulator biases. A maximum bandwidth of 35 GHz was observed at -2 V DC bias, at which point the waveguide is fully depleted (Fig. 5).

A 40 Gbps signal with 2.5 V_{p-p} from a SHF BERT was used to drive the modulator. Eye diagrams with a $\sim$0.24 mW

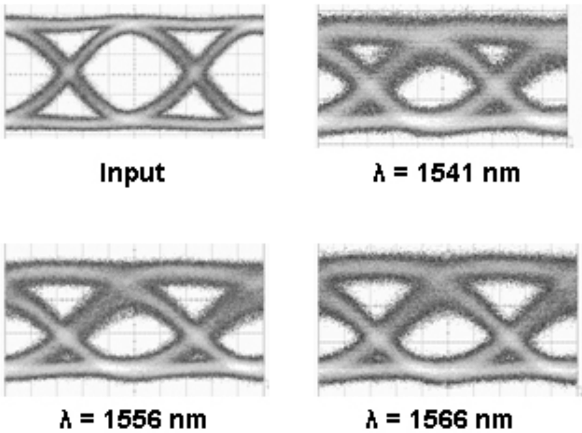

Fig. 6. Eyes at 40 Gbps for 2^7-1 PRBS and V_{p-p} = 2.5 V. (λ = 1541 nm, V_{MZ1} = V_{MZ2} = -1 V, P_{out} = 0.240 mW, Extinction Ratio = 7.8 dB; λ = 1557 nm, V_{MZ1} = V_{MZ2} = -1.5 V, P_{out} = 0.249 mW, Extinction Ratio = 9.0 dB; λ = 1566 nm, V_{MZ1} = V_{MZ2} = -1.5 V, P_{out} = 0.241 mW, Extinction Ratio = 7.8 dB)

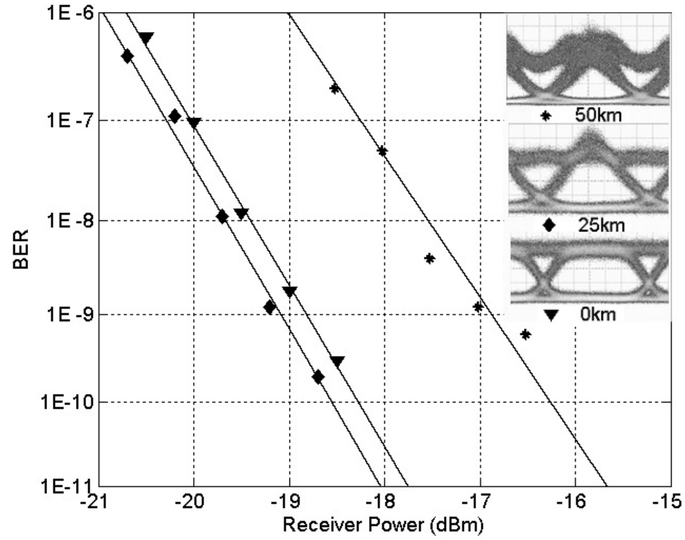

Fig. 7. BER vs. receiver power at 10 Gbps for a wavelength of 1541 nm. BER measurements were taken for transmission through 0 km, 25 km and 50 km of Corning SMF-28 fiber. (V_{p-p} = 1.87 V; V_{MZ1} = V_{MZ2} = -1 V)

power swing demonstrated extinction ratio values of 7.9-9.0 dB across the 25 nm tuning range (Fig. 6). The modulator was biased at -1.5 V for 1556 nm and 1566 nm, while -1 V was required at 1541 nm due to increased insertion losses.

Bit Error Rate testing at 10 Gb/s with a NRZ 2^{31}-1 pseudorandom bit sequence was done across the tuning range for both back-to-back and transmission through 25 km and 50 km of Corning SMF-28 fiber. The modulator was biased at -1 V across each arm and driven with a 1.87 V_{p-p} electrical signal from a HP 70843B BERT. The optical signal from the device was amplified with a high power Erbium Doped Fiber Amplifier (EDFA) followed by an optical filter, fiber for transmission, and an attenuator before being detected by an HP 83434A 10 Gb/s photoreceiver. Error free operation (better than 1e-9 BER) and extinction ratios in excess of 10 dB were achieved across a wavelength range greater than 25 nm. Fitting the data to the relationship between power penalty and distance described in [7] was used to calculate the chirp values. Transmission power penalties corresponding to chirp values of -0.28, -0.46 and -0.96 were measured for wavelengths of 1568 nm, 1556 nm and 1541 nm respectively (Fig. 7).

IV. Conclusion

A widely tunable Mach-Zehnder transmitter has been fabricated on a dual-quantum-well platform utilizing waveguide quantum wells for index modulation. The device demonstrates a bandwidth in excess of 35 GHz and at 40 Gbps extinction ratios $>$ 7.8 dB are seen across the wavelength range of 1541 nm to 1566 nm. Error free operation at 10 Gbps has been demonstrated for up to 50 km of transmission through fiber and all wavelengths have negative chirp with a 1.87 V_{p-p} drive voltage.

References

[1] K. Tsuzuki, K. Sano, N. Kikuchi, N. Kashio, E. Yamada, Y. Shibata, T. Ishibashi, M. Takumitsu, and Y. Yasaka, "0.3 v_{pp} single-drive push-pull inp mach-zehnder modulator module for 43-gbit/s systems," in *Optical Fiber Communication Conference and Exposition and The National Fiber Optic Engineers Conference*, Anaheim, CA USA, March 2006, paper OWC2.

[2] S. Akiyama, S. Hirose, T. Watanabe, M. Ueda, S. Sekiguchi, N. Morii, T. Yamamoto, A. Kuramata, and H. Soda, "Novel inp-based mach-zehnder modulator for 40 gb/s integrated lightwave source," in *IEEE 18th International Semiconductor Laser Conference*, 2002, pp. 57–58.

[3] J. S. Barton, M. L. Masanovic, A. Tauke-Pedretti, E. J. Skogen, and L. A. Coldren, "Monolithically-integrated 40 gbit/s widely-tunable transmitter using series push-pull mach-zehnder modulator soa and sampled-grating dbr laser," in *Optical Fiber Communication Conference and Exposition and The National Fiber Optic Engineers Conference*, Anaheim, CA USA, March 2005, paper OTuM3.

[4] W. Bardyszewski, D. Yevick, L. Yong, C. Rolland, and S. Bradshaw, "Theoretical and experimental analysis of mach-zehnder quantum-well modulators," *Journal of Applied Physics*, vol. 80, pp. 1136–41, July 1996.

[5] M. N. Sysak, J. W. Raring, J. S. Barton, M. Dummer, D. J. Blumenthal, and L. A. Coldren, "A single regrowth integration platform for photonic circuits incorporating tunable sgdbr lasers and quantum well eams," *IEEE Photon. Technol. Lett.*, p. accepted, 2006.

[6] R. G. Walker, "High-speed iii-v semiconductor intensity modulators," *IEEE J. Quantum Electron.*, vol. 27, pp. 654–667, Mar. 1991.

[7] G. P. Agrawal, *Fiber-optic Communication Systems*, 3rd ed. John Wiley and Sons, Inc., 2002.