High-Power Intrastep Quantum Well Electroabsorption Modulator Using Single-Sided Large Optical Cavity Waveguide

J. X. Chen, Y. Wu, W. X. Chen, I. Shubin, A. Clawson, W. S. C. Chang, and P. K. L. Yu

***Abstract*—A novel electroabsorption modulator (EAM) using intrastep quantum wells (IQWs) and a single-sided large optical cavity waveguide is demonstrated to operate at up to 100 mW of input optical power. When the IQW EAM with uncoated facets is tested in an analog fiber link, the radio-frequency link gain reaches −16.1 dB at 100-mW optical power. We have measured a single-octave spurious-free dynamic range (SFDR) of 121 dB · $Hz^{4/5}$ and multioctave SFDR of 110 dB · $Hz^{2/3}$ for this EAM.**

***Index Terms*—Analog fiber link, electroabsorption, high power, intrastep quantum well (IQW), large optical cavity (LOC), modulator.**

ANALOG fiber links are useful for applications such as distribution of cable television signals, antenna remoting of cellular stations, and beam forming for phased-array radars [1]. The electroabsorption modulator (EAM) has been considered for these links due to its potential for low power consumption, compact size, and ease to integrate with other semiconductor devices. Three primary figures of merit are used to characterize the performance of EAM: radio-frequency (RF) link gain, two-tone spurious-free dynamic range (SFDR), and noise figure. This work focuses on novel device design for high link gain. For an RF input-matched device, it can be expressed as [1]

$$G = P_{\text{opt}}^2 t_{\text{ff}}^2 \eta^2 R_{\text{in}} R_{\text{out}} \left(\frac{\pi}{2V_\pi} \right)^2 \quad (1)$$

where P_{opt} is the optical input power to the EAM, t_{ff} is fiber-to-fiber transmission coefficient of EAM, η is the responsivity of detector, R_{in} is the RF source impedance, and R_{out} is the output resistance of detector. For EAM with unmatched electrode, a factor of ∼4 is typically incorporated in (1) to account for the voltage enhancement caused by the microwave reflection. The equivalent V_π is defined as

$$V_\pi = \frac{\pi}{2} \left(\frac{\partial T_N}{\partial V} \right)^{-1} \quad (2)$$

where $\partial T_N / \partial V$ is the slope efficiency of normalized EAM transfer curve. Thus, the higher the slope efficiency, the smaller V_π is.

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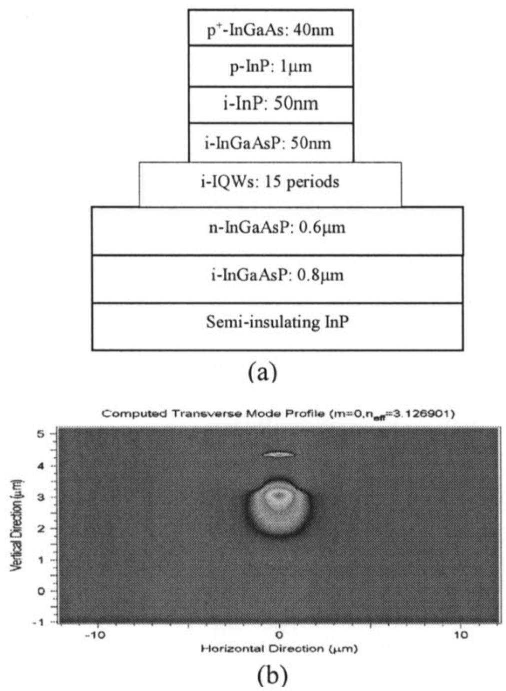

Fig. 1. (a) Layer structure of the IQW EAM (not in scale). (b) Simulated mode profile with expanded width in the vertical direction.

The basic approaches to obtain a high link gain in an externally modulated link are to have low insertion loss, high optical power handling, and high slope efficiency at the modulator. We have previously proposed to use the intrastep quantum well (IQW) to increase the biasing electric field at the electroabsorption region for sweeping out carriers at high optical power [2]. The IQW has the additional merit of large quantum confined Stark effect (QCSE) [3]–[5], which implies small drive voltage. Our previous IQW EAM was limited by the available materials and the waveguide design that resulted in devices with a large optical insertion loss of ∼20 dB [6].

Since the optical waveguide design of the EAM is very critical for the optical insertion loss, we have adopted in this work a waveguide design that reduces the propagation loss and the coupling loss due to mode-mismatch. It consists of a single-sided large optical cavity (LOC) layer underneath the IQW electroabsorption region. In doing so, we demonstrated that very high power operation, low insertion loss, and high slope efficiency can be achieved with IQW EAM.

The present IQW-EAM is based on InGaAsP–InP materials grown by metal–organic vapor phase epitaxy. The material structure is depicted in Fig. 1(a) that has several features

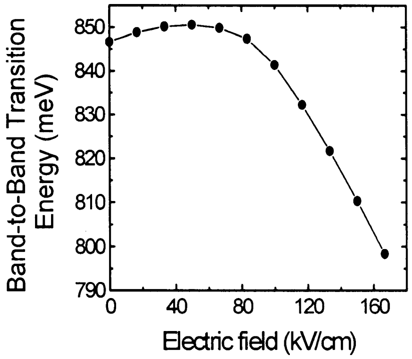

Fig. 2. Transition energy between first heavy hole subband to first conduction subband as a function of the electric field.

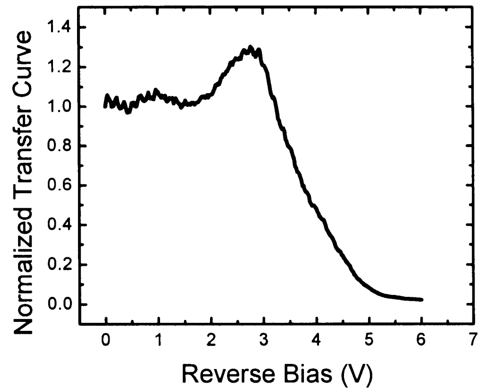

Fig. 3. Normalized dc transfer curve measured with optical input power of 10 mW.

designed for very high power operation. Most notable is the 1.4-μm-thick InGaAsP waveguiding layer (with bandgap wavelength of 1.1 μm) grown between the semiinsulating InP substrate and the IQW electroabsorption region. To reduce the free carrier absorption, only the top 0.6-μm portion is n-doped while the remaining 0.8-μm is undoped.

The LOC layer widens the optical mode in the vertical direction so that the mode shape becomes more rounded. This results in good modal overlap with the circular mode profile of single-mode fiber. Also, as the mode center is near the LOC layer, only the tail region of the mode reaches the sidewall of the waveguide. Consequently, when compared to the conventional ridge waveguide, the present design has smaller modal scattering loss.

The simulated mode profile is shown in Fig. 1(b) for a device with a top ridge of 1.14 μm. It should be noted that this LOC design can reduce the optical confinement factor of the electroabsorption region, and thus, potentially increases the V_π for EAM with limited length. However, a small confinement factor is also desirable for high optical power handling, as a relatively smaller fraction of the optical intensity is then absorbed at the intrinsic IQW layer, especially important at the front end of the waveguide. An optimization of the layer thickness and composition of the LOC layer with respect to the rest of structure has been done by simulation to increase the RF link gain. The 1.4-μm thickness of the waveguiding layer is presently limited by the epitaxial growth.

The single-sided LOC structure is different from the double-sided LOC, where LOC layers are placed on both sides of the modulation region and a mesa is formed at the upper waveguide layer. The latter structure also aims at reducing the coupling loss. However, we found that the present single-sided LOC has a relatively smaller insertion loss when compared to the double-sided LOC and easier fiber alignment.

For this sample, 15 periods of IQWs are incorporated in the intrinsic layer, with the barrier, intrastep-barrier, and well layers having thickness of 7, 6, and 5 nm, respectively. By numerically solving Schrödinger's equation using effective mass and envelope function approximations, we estimate a zero-field exciton transition wavelength of 1465 nm between the first heavy hole subband and the first conduction subband, and its variation with the applied field is shown in Fig. 2. The slight blue shift at low field is characteristic of IQW [2], [6]. At field >60 kV/cm, the QCSE becomes dominant and the exciton resonance is red-shifted and broadened. IQW EAM can handle high power because the large electroabsorption occurs at a higher electric field [6]. Above the IQW layer is a separate electric field confinement layer, consisted of undoped 50-nm InGaAsP and 50-nm InP, for reducing the valence band offset between the p-InP and IQW absorption layer that can block the swept-out of photogenerated holes. This layer also served as a barrier against zinc diffusion into the multiquantum well layers.

The IQW sample is processed into waveguide EAMs with 2.5-μm-wide top ridge. Device sidewalls are passivated with polyimide. Metal electrodes with lumped-element electric circuit representation are thermally evaporated on top of p and n layers. Fig. 3 shows the normalized dc transfer curve with 10 mW of optical input power. The device measured has the ridge waveguide dimensions of $2.5 \times 350\ \mu m^2$. The light source consists of a tunable laser with wavelength tuned to 1543 nm, whose output is amplified with an Erbium-doped fiber amplifier (EDFA). The input light to the IQW EAM is transverse electric (TE)-polarized.

Due to the characteristics of IQW, electroabsorption at small reverse bias (<3.2 V, in this case) is suppressed [6]. At a large enough bias (>3.2 V), a large absorption occurs. At high optical input level (10 mW or higher), the transfer curve shows a negative slope efficiency at bias between 2 and 3 V. We believe this is caused by saturation at low field, as suggested by the modulator photocurrent characteristics. This saturation effect is largely absent at high bias (>3 V) until very large optical power is used.

The optical insertion loss of the EAM at zero bias is measured at −11.9 dB without antireflection (AR) coating. It is approximately 1 dB smaller at the peak of the 10-mW curve (see Fig. 3). The best insertion loss obtained in our experiment is −7.6 dB for wavelength of 1553 nm, polarized at transverse-magnetic (TM) mode. However, the transfer curve of TE mode has a higher slope efficiency than the TM mode, due to the nondegeneration of the light hole and heavy hole subband in the quantum well. When the transfer curve is normalized with respect to the zero-bias value, the equivalent V_π is measured at 1.1 V for a 350-μm-long waveguide.

To characterize the optical power handling capability, the RF link gain at different optical powers is measured at the laser wavelength of 1543 nm. The power of the laser is boosted up

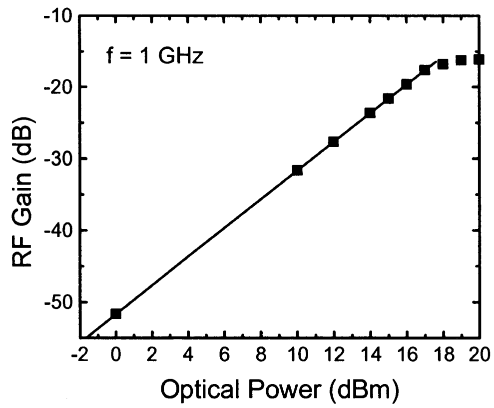

Fig. 4. RF gain of analog optical link measurement of the IQW EAM.

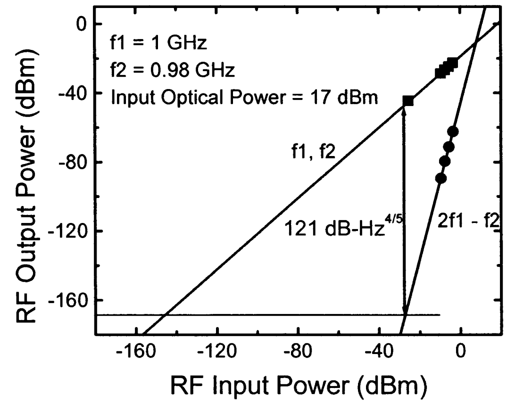

Fig. 5. Two-tone single-octave SFDR measurement of the IQW EAM.

by EDFA, ranging from 1 to 100 mW. A 1-GHz RF signal with power of -11.35 dBm is used to modulate the EAM. The detector responsivity is $\sim$0.7 A/W. As shown in Fig. 4, the link gain increases linearly in the log scale with slope of two, consistent with (1). The 1-dB compression point occurs at 60-mW input optical power, where the RF gain is around -17.0 dB. When the injected optical power goes up to 100 mW, RF gain of -16.1 dB is observed. These results, to our knowledge, are the highest input optical power reported for multiquantum well EAM without heat sink. A higher link gain is expected when AR-coating is applied at the facets of the waveguide. The observed gain saturation is attributed to the thermal effect of the polyimide passivation present along the waveguide.

We have also characterized the two-tone SFDR for this IQW EAM. The optical input power to the EAM is 50 mW and the bias voltage is 3.3 V. The two RF tones are at 1 and 0.98 GHz, respectively. According to the insertion loss at bias point and input optical power, we estimate that the shot-noise-dominated noise floor is -168 dBm. The two-tone single-octave SFDR is 121 dB $\cdot$ $\text{Hz}^{4/5}$, as shown in Fig. 5. By minimizing the second-order harmonic at the optimized bias, we obtained a multioctave SFDR of 110 dB $\cdot$ $\text{Hz}^{2/3}$ for this device.

In summary, we have demonstrated an IQW EAM structure with a single-sided LOC waveguide that has high power, low insertion loss, and small equivalent V_π properties. The 1-dB compression point of RF link gain occurs at an optical input power of 60 mW, where the link gain is -17.0 dB. The EAM can handle input optical power as high as 100 mW and gives -16.1-dB link gain. Two-tone SFDRs of 121 dB $\cdot$ $\text{Hz}^{4/5}$ and 110 dB $\cdot$ $\text{Hz}^{2/3}$ are measured for single-octave and multioctave applications, respectively.

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