Reflective Semiconductor Optical Amplifier Electrode Voltage based Phase Shifter Model

M. J. Connelly

Optical Communications Research Group, Dept. Electronic and Computer Engineering, University of Limerick, Limerick, Ireland. E-mail: michael.connelly@ul.ie.

***Abstract*- The slow light effect in semiconductor optical amplifiers has many applications in microwave photonics such as phase shifting. An amplified sinusoidally amplitude modulated lightwave leads to carrier density fluctuations at the modulation frequency. This leads to a change in the effective group index and after photodetection the beat signal (at the modulation frequency) at the output is phase shifted relative to the input beat signal. A potential alternative scheme is to use the detected electrode voltage as the photodetector. The voltage depends on dynamic changes in the conduction-valence band quasi-Fermi level difference. The feasibility of the proposed scheme, using bulk reflective SOA, is shown by using a time-domain model that includes band-structure based calculations of the SOA material properties, a carrier density rate equation, and travelling-wave equations for the amplified signal and spontaneous emission.**

I. INTRODUCTION

[*] There is an increasing interest in exploiting the possibility of controlling the group velocity of light [1]. Slow light occurs when a propagating pulse is slowed down by interaction with the medium in which the propagation takes place. Slow light has potential applications in microwave photonics such as tunable phase shifters [2]. In an SOA the principle mechanism causing the slow light effect is coherent population oscillations (CPOs), whereby beating between two lightwaves leads to carrier density oscillations at the beat frequency. This leads to a change in the group index and so the beat signal at the output is phase shifted relative to the input beat signal. RSOAs have a lower operating current than traveling-wave SOAs and are also easier to saturate so functions based on SOA non-linearities are easier to achieve. SOA slow-light microwave phase shifters usually use traveling-wave SOAs followed by a photodetector. Recently we described the experimental characterization and modeling of an RSOA slow-light based phase shifter [3]. In this paper, we model a potential alternative scheme that uses the detected electrode voltage as the photodetector. The electrode voltage depends on dynamic changes in the conduction and valence quasi-Fermi level difference induced by an amplified sinusoidally amplitude modulated input lightwave.

[*] This research was supported by Science Foundation Ireland Investigator Grant 09/IN.1/I2641.

II. THEORY AND NUMERICAL MODEL

The RSOA is a commercially available tensile-strained bulk InGaAsP/InP device (Kamelian) [4]. The active waveguide consists of an 80 μm long input taper (with a width varying linearly from 0.45 μm to 1.2 μm) followed by a 270 μm straight section. The small-signal gain and saturation output power at a bias current of 100 mA and signal wavelength of 1551 nm are 22 dB and of 5 dBm respectively. Material parameters used in the model can be found in [5, 6]. The input and reflective facets have reflectivities of 5×10^{-5} and 0.88 respectively. The input lightwave signal is a double-sideband unsuppressed carrier signal, so the envelope of the input optical field is given by

$$E(t)=\sqrt{P_c[1+m\cos(2\pi f_m t)]} \tag{1}$$

, where P_c is the carrier power, m is the modulation index and f_m is the modulating (beat) frequency. The SOA dynamics are governed by the interaction between the amplified signal, amplified spontaneous emission (ASE) and carrier density. In the model the relevant dynamics occur on time scales much greater than the SOA transit time (~8.5 ps) so the optical fields can be assumed to propagate instantaneously across the SOA length. The active region carrier density n rate equation [3, 6] is

$$\frac{dn}{dt}=\frac{\eta I}{eV}-R(n)-\frac{\Gamma_{s,p}}{dW(z)}g_{m,TE/TM}I^{\pm}_{s,TE/TM}-\frac{1}{dW(z)}\sum_{TE,TM}\sum_{k=1}^{M}\Gamma_{TE/TM}(z)g_{m,TE/TM,k}N^{\pm}_{TE/TM,k}(z) \tag{2}$$

The terms on the RHS of (2) are the current pump, spontaneous and Auger recombination, and carrier depletion due to the forward and backward propagating amplified signal $I^{\pm}_{s,TE/TM}$ and ASE $N^{\pm}_{TE/TM,k}$ (k-th spectral slice) photon rates. g_m is the active region material gain, determined using a full bandstructure model [5]. z is the distance from the SOA input facet. The model uses M = 264 spectral slices spanning a wavelength range of 300 nm centered at 1550 nm. The electrode voltage $v(z)$ at z is equal to the carrier density dependent quasi-Fermi level difference $\Delta E_{cv}[n(z)] = E_{fc}[n(z)] - E_{fv}[n(z)]$ divided by the electronic charge e. The detected voltage $v_{\det}$ is $v(z)$ averaged over the amplifier length L,

$$v_{\det} = \frac{1}{L}\int_0^L v(z)\,dz = \frac{1}{L}\int_0^L e^{-1}\Delta E_{cv}[n(z)]\,dz \qquad (3)$$

The electrode voltage sensitivity to carrier density dv/dn, obtained from the quasi-Fermi level calculations, including bandgap shrinkage, is shown in Fig. 2. $I^{\pm}_{s,TE/TM}$ and $N^{\pm}_{TE/TM,k}$ are determined by the traveling-wave equations [3, 6],

$$\frac{dI^{\pm}_{s,TE/TM}}{dz} = \pm g_{TE/TM}\, I^{\pm}_{s,TE/TM} \qquad (4)$$

$$\frac{dN^{\pm}_{TE/TM,k}}{dz} = \pm g_{TE/TM,k}\, N^{\pm}_{TE/TM,k} \pm R_{sp,TE/TM,k} \qquad (5)$$

, taking into account the boundary conditions at the reflecting facets. R_{sp} accounts for additive spontaneous emission. $g_{TE/TM}$ is the net gain coefficient, including the optical confinement factor and the scattering loss. The differential equations are solved using finite difference techniques. The dynamic detected voltage can then be obtained using (3).

III. SIMULATIONS

A steady-state model was used to determine the ASE spectra and gain characteristics [6]. As shown in Fig. 1 there is good agreement between experiment and simulation, which gives confidence in the application of the dynamic model.

Fig. 3 shows typical dependencies of the detected voltage frequency response for a small modulation index. Fig. 3(a) shows that the frequency response has a low pass characteristic, which is due to the finite carrier lifetime. This lifetime is inversely proportional to carrier density, which decreases as the bias current increases. The simulations can be used to determine the electrode small-signal resistance which is approximately $3\,\Omega$. Inserting a $47\,\Omega$ resistor will allow impedance matching to an external $50\,\Omega$ load via a lossless $50\,\Omega$ transmission line. Fig. 3(b) shows the electrical power dissipated by the load. Fig. 3(c) shows the phase response. At low frequencies, there is almost complete inversion of the beat signal. As the frequency increases the phase shift tends towards 90°. Over the current range of 50 to 100 mA the phase can be tuned by approximately 10°. Wider tuning is possible by changing the input optical power and modulation index.

IV. CONCLUSIONS

In this paper the feasibility of using the detected electrode voltage as a microwave phase shifter has been shown using numerical simulations.

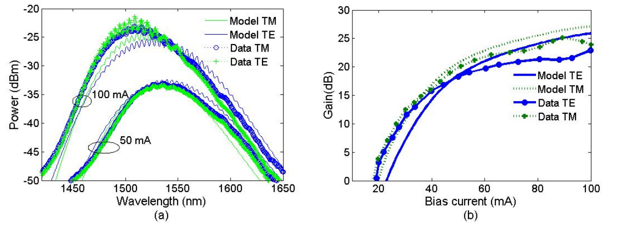

Fig. 1. (a) TE and TM ASE spectrums with no input signal present. (b) Gain vs. current for a signal wavelength of 1550 nm and input power of -25 dBm. R

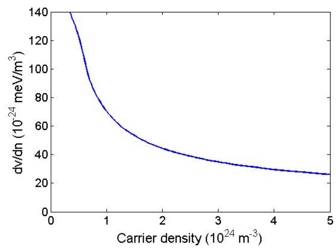

Fig. 2. (a) Electrode voltage sensitivity to carrier density.

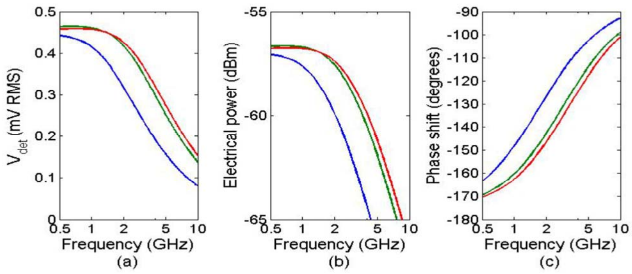

Fig. 3. Phase shifter (a) RMS detected voltage, (b) electrical power into 50 Ω impedance matched load and (c) Phase shift. Blue, green and red lines are for 50 mA, 75 mA and 100 mA currents respectively. The input optical power and modulation index are -3 dBm and 5% respectively.

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