An ultrafast InP/InGaAs Poptical modulator

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Embedding a Bragg reflector in an optoelectronic modulator could overcome the 40Gbit/s speed limit.

Direct-bandgap III-V semiconductor materials based on InP allow monolithic integration of optical functionality with electronic circuitry for optical communication applications.¹ The quaternary III-V alloy, InGaAsP, is particularly important because its bandgap can be tuned to different wavelength windows by adjusting its composition, while keeping its lattice matched to InP. Optoelectronic modulators, which translate electrical pulses into light pulses, are a critical component for communications. Here we show how, by electrically inducing a 2.5mm-long Distributed Bragg Reflector² in an InP/InGaAsP waveguide, we can theoretically realize a modulator capable of a switching speed over 40GHz. The proposed device, shown in cross section in Figure 1, is a vertical InP/InGaAsP *p-i-n* diode, in which the intrinsic InGaAsP layer defines the optical channel. The anode is periodically spaced along the top of waveguide, as shown in schematic top view in Figure 1.

The principle of operation is straightforward. When the diode is unbiased, the device is transparent and light can travel along the modulator without being affected by loss. When a negative voltage is applied between anode and cathode, a Bragg reflector is induced, due to the periodic refractive-index variation in the intrinsic region caused by spatial periodicity of the anode along the 2.5mm waveguide. The periodic index variation causes the light to be reflected rather than transmitted.

When an electric field is applied to a semiconductor, two main types of effect can induce a refractive-index variation: the first is related directly to electric field strength (electro-optic effect), while the other type includes several effects related to the change of the free-carrier concentration. In InP-based materials, no single effect is dominant.

To predict grating reflectivity, it is necessary to know how the effective index of the junction varies with the applied anode bias. The first step is to compute the refractive-index variation in the

Figure 1. The left panel shows a schematic cross-section of the proposed modulator, where the guiding layer is intrinsic InGaAsP. The top signal electrode (the anode) is patterned into a comb-like shape, as shown in the top view of the device on the right.

guiding region. To evaluate the carrier-induced effects like band filling and plasma, we need to evaluate the carrier concentration by means of an electronic simulator. The refractive-index change, taking all the effects into account, can be then evaluated by means of finite-element modeling (FEM).

For this purpose we use in-house code³ based on a simulation strategy that takes advantage of state-of-the-art electronic simulator, such as Silvaco/ATLAS, and a general purpose FEM solver, such as Comsol Multiphysics. The code allows us to use the same mesh to evaluate all the quantities of interest, including the effective index. First we map, by means of ATLAS, the variation of the electronic parameters in the device (electron and hole concentration and electric-field distribution), varying the applied electric field between anode and cathode, i.e. the bias voltage V . Second, we import the ATLAS mesh grid and the data on this grid into the FEMLAB program to compute the effective refractive indices of the rib guide's fundamental TE and TM modes, as a function of the anode bias. Fortunately, due to the geometry of the device and the crystal-plane alignment, only the vertical component of the applied e-field is relevant, so a scalar approach has been followed in the solution of the wave

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Figure 2. The calculated reflectivity of the modulator rises as the reverse bias is increased for both TE and TM polarization.

equation. Finally, the grating reflectivity is computed using the impedance-matching-matrix method⁴ by means of MATLAB.

To clarify the DC behavior of this modulator, we show in Figure 2 the optoelectronic transfer curve, that is, the relationship between reflectivity and applied voltage for both polarizations.

Choosing the maximum bias to be applied to the device requires a tradeoff. Higher voltages increase the electric field and therefore the phase-shift per unit length. On the other hand, as we increase the negative bias we get closer to avalanche breakdown of the junction and consequent injection of free carriers into the optical channel. The other option is to make the device longer and thus reduce the applied voltage, at a cost of higher propagation losses. By trading off these two constraints we settle on a 2.5mm-long modulator and a maximum bias of -10V to be applied on the anode. We emphasize that, due to the comb structure of the anode contact, a 2.5mm-long device presents the same capacitance as a 1.25mm-long fully-covered electrode.

To verify the theoretical switching capability of this device, a negative square voltage pulse was applied to the anode and its reflectivity evaluated. The result of this simulation is reported in Figure 3. We can see a very-fast rise and fall transient (an average of 3ps) that suggests the device could be used for 40Gbit/s modulation. This switching speed is obviously a theoretical upper limit, because the driving amplifiers have to be impedance-matched to the modulator.

Conclusion

We have shown that it is possible to built an optoelectronic modulator that is potentially capable of 40GHz switching speed by inducing a Bragg Reflector in an reverse-biased vertical

Figure 3. The calculated transient behavior of the proposed modulator, when driven by a 15ps-long -10V pulse, exhibits rise times estimated to be about 0.8ps.

InP/InGaAsP *p-i-n* diode. The grating reflectivity spectra and the transient response were calculated using in-house code, based on a state-of-the-art electronic simulator and a general purpose FEM solver, which allows us to use the same grid for electronic and optical simulations.

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