All-optical low-power switch based on III-V/SOI heterogeneous integration

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Abstract: We propose an integrated all-optical switch with a low operating power that allows continuous wave operation. To achieve switching in an efficient way, we use the free carrier dispersion effect in a III-V multi-quantum well layer bonded on a Silicon on Insulator ring resonator. Using Mach-Zehnder interferometers for coupling light in and out the ring, we theoretically show that switching with an extinction ratio of 10dB at a pump power of only 300μW is achievable.

Keywords: All-optical switch, heterogeneous integration

Introduction

In silicon, all-optical switching using ring resonators has already been demonstrated. The switching relies on the free carrier dispersion (FCD) effect, in which the refractive index of silicon decreases with increasing carrier density. In these earlier designs, one used either a pulsed blue pump laser illuminating the resonator from the top to create carriers by single-photon absorption (SPA) [1] or one coupled a pulsed pump at telecom wavelengths in the ring, with a high enough intensity to create carriers by two-photon absorption (TPA) [2]. A disadvantage of these designs is that continuous wave operation is impossible. This is due to the fact that, given the relatively high power consumption, the device heats up and as a consequence the thermo-optic effect in silicon counteracts the FCD effect.

In this paper, we propose an all-optical switch that is also based on the FCD effect, but now in a III-V multi-quantum well layer stack bonded on top of the silicon resonator. The bonding can be done using DVS-BCB bonding [3]. This setup has the advantage that we can use SPA of a telecom wavelength pump laser for carrier generation in the III-V layer, so the required light intensity in ring is much lower than for devices using TPA. Furthermore, the coefficient of the FCD effect of the quantum well material ($1\text{x}10^{-20}/\text{cm}^3$) is an order of magnitude larger than for silicon. This means that we will need less carriers for equal performance, so less pump power will be required. These two advantages reduce the dissipated power and thus reduce the magnitude of the thermo-optic effect, enabling continuous wave operation.

2. Cavity structure

To use the pump power as efficiently as possible, we use a ring structure as shown in figure 1. The Mach-Zehnder interferometers can then be optimized to achieve the following steady state behaviour. The top Mach-Zehnder should couple the pump critically in the cavity. The bottom Mach-Zehnder should couple the signal light critically in the cavity when the pump is on but on the other hand should not couple any pump light out of the cavity. These conditions should be combined with the resonance condition for both signal (λ_s) and pump (λ_p) wavelengths. These requirements yield a family of ring structures suitable for all-optical switching.

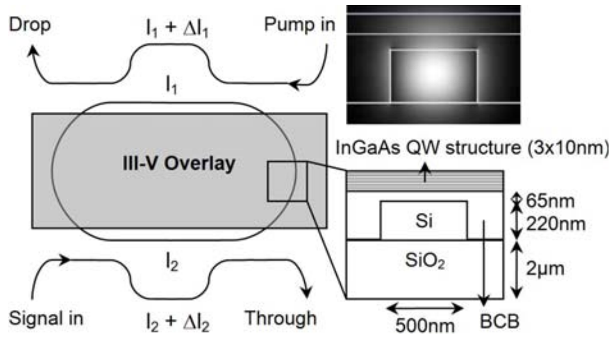

Figure 1 : Structure of all-optical switch. The inset in the top right corner shows the field in the waveguide. Most of the light is confined in the silicon core, the confinement in the quantum wells is only 4.5%.

3. Non-linear effects

The proposed all-optical switch uses the FCD effect in the quantum well material to achieve switching. The equation that governs the carrier density in the quantum wells is given by

$$\frac{\partial N_{qw}}{\partial t} = \frac{P_{abs}}{h\nu V_{qw}} - \frac{N_{qw}}{\tau_{qw}} \qquad [2]$$

with P_{abs} the absorbed power by SPA in the quantum wells and τ_{qw} the effective lifetime of the carriers (280ps). This quantity includes carrier diffusion and drift effects in the case a lateral electric field is applied which further reduces the effective lifetime. TPA in the quantum wells is neglected, as the intensity is low here (see inset figure 1).

However, there will also be some creation of carriers in Si, because of TPA. This effect induces direct heating of the structure and the creation of extra losses due to free carrier absorption (FCA). It is governed by the following equation

$$\frac{\partial N_{Si}}{\partial t} = \frac{P_{TPA}}{2h\nu V_{Si}} - \frac{N_{Si}}{\tau_{Si}} \qquad [3]$$

τ_{Si} (500ps) is the effective carrier lifetime in the Si core, which is determined by surface recombination at waveguide edges.

A second important effect is the heating of the structure. We calculate the temperature change as follows

$$\frac{\partial \Delta T}{\partial t} + \frac{\Delta T}{\tau_\theta} = \frac{P_{diss}}{\rho C_p V} \qquad [4]$$

The thermal timeconstant τ_θ depends on the fraction of the ring covered with the III/V layer. For the design where we will show some results for, it is calculated to be 120ns, using finite element modeling.

P_{diss} is the total dissipated power

$$P_{diss} = \frac{h\nu_p - E_g}{E_g} P_{abs} + P_{TPA} + P_{FCA} \qquad [5]$$

with E_g the bandgap of the quantum wells. All power absorbed by TPA in the Si core and by FCA is converted to heat. There is also a small fraction of P_{abs} that is dissipated due to thermalisation of the created carriers. Most of the absorbed power is however converted to light again, because the radiative lifetime in the quantum wells is much lower than the non-radiative lifetime.

To be able to calculate the static and dynamic behaviour of the proposed switch, one still needs to calculate the absorbed powers P_{abs}, P_{TPA} and P_{FCA}. For this, we use the following relation

$$\frac{\partial I}{\partial z} = -\left[\Gamma_{qw}(\alpha_{OPA} + \alpha_{fr,qw}) + \Gamma_{Si}\alpha_{fr,Si} + \alpha_{sc}\right] I(z) - \beta_{TPA} I(z)^2 \qquad [8]$$

Integrating this equation using the appropriate boundary conditions yields I(z) and hence P_{abs}, P_{TPA} and P_{FCA}.

A typical curve illustrating the wavelength shift as a function of pump power is shown in figure 2 showing the initial blueshift of the resonance which is counteracted by thermal redshift at higher pump powers. This was also experimentally observed in [3].

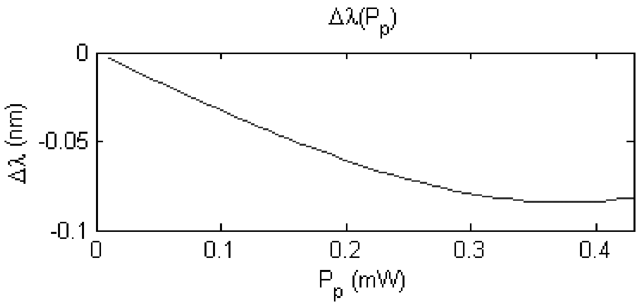

Figure 2: Δλ as a function of the pump power

4. Simulation results

Using the above model, we have optimized the device lay-out for steady state operation. A three quantum well layer stack (bandgap wavelength 1.55µm) is used, resulting in a quantum well confinement factor of 4.5%. This means that the maximal achievable wavelength shift will be limited. However, it is still feasable to obtain continuous wave switching operation with an extinction ratio of 10dB. The transferfunctions of an optimized all-optical switch are shown in figure 3 around a signal wavelength of 1.56µm, showing the switching behaviour using a 430µW pump at a wavelength of 1.52µm. As the Q-factor of the resonator is quite high, the bandwidth of this device is limited to 5GHz. However, high agregate bitrate switching can be obtained by using a comb switch [1]. This has the disadvantage however that the required pump power increases, since such a device needs a small free spectral range and thus a longer ring, so a longer active section needs to be pumped.

We have also simulated the dynamics of the switching behaviour and we have found that the speed is limited by τ_{qw}. However, because the thermal effect is slower, it takes a while until the steady state situation is reached. This can be solved by shaping the pump pulse: one should start with a lower pumppower and gradually increase it to the steady state value to achieve a constant Δλ independent of τ_θ.

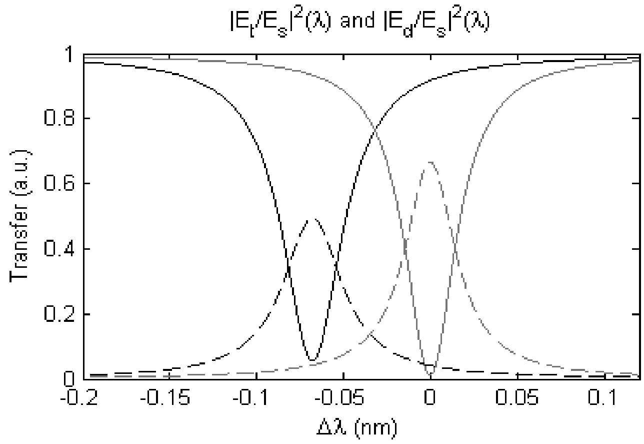

Figure 3: transferfunctions. The grey functions are without pump, the black with pump (430µW). The dashed line is $|E_d/E_s|^2$, the solid line $|E_t/E_s|^2$.

5. Conclusion

We proposed a low power consumption all-optical switch based on III-V/SOI heterogeneous integration, based on the FCD effect in III-V quantum wells. Further performance improvement can be expected by the use of silicon slotted waveguides [4] to reduce the TPA in the waveguide core and to increase the confinement factor in the quantum wells.

6. Acknowledgment

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7. References

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