Modeling of an optical memory based on tunable lasers suitable for optical integrated circuits

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Simulations of two laser systems of which the output wavelength can be switched by optical pulses are presented. The first system is based on two laser cavities containing a phased array waveguide (PHASAR) grating and an optical amplifier, that are coupled with a third optical amplifier. The second system consists of a single laser that contains a PHASAR, amplifier and two or more saturable absorbers. The rate equation model shows that the systems can be switched using pulses with a specific amount of energy. Switching speeds, requirements on the control pulses and the relation with design parameters are discussed.

Introduction

In optical telecommunication networks one would like to have optical memory, in particular for packet switching type networks. In an optical memory cell one can store the information that an optical pulse (possibly one with particular properties) has arrived, and this information is thereafter continuously available in some optical form. An optical memory is typically a bi-(or multi)stable device that be in two (or more) states and that can switch states using an optical pulse. The devices that are discussed here are laser systems that produce a specific wavelength associated with each state. An externally generated optical pulse can switch this output wavelength. In the cases presented here the incoming pulse has the wavelength of the state that we would like to have the memory set to. As such these devices are wavelength memory cells and are essentially tunable laser systems that can be switched quickly between wavelengths, which is another desirable device for WDM telecommunication networks.

The results obtained in the OED group on integrated wavelength switchable lasers using the butt-joint active-passive integration technology make that we can now start to design optically integrated memory cells based on this type of lasers. This paper discusses the rate equation modelling of two possible designs for optical memory based on laser systems that we are able to integrate using our existing technology in the InP/InGaAsP material system. The purpose of this modelling is to help us with the design of the on-chip devices.

Coupled laser cavities memory

The first system is similar to the device by Hill et al [1]. A diagram of the device in its two possible states is given in figure 1. Here the device is depicted in its two possible states. The device consists of two laser cavities, each containing an SOA, a phased array multiplexer (PHASAR) and two mirrors (M) that will typically be end facets. If in cavity 1 (with SOA 1) the laser is operating it will produce light at wavelength λ1, determined by the PHASAR [2]. The part of the power from the cavity is led through an amplifier (SOA 3) and injected into SOA 2 that is included in cavity 2. The light at λ1 saturates

SOA 2 and makes that this laser cavity, which can only operate at λ2, is below threshold. The amplified light at l1 then passes through the PHASAR This is the

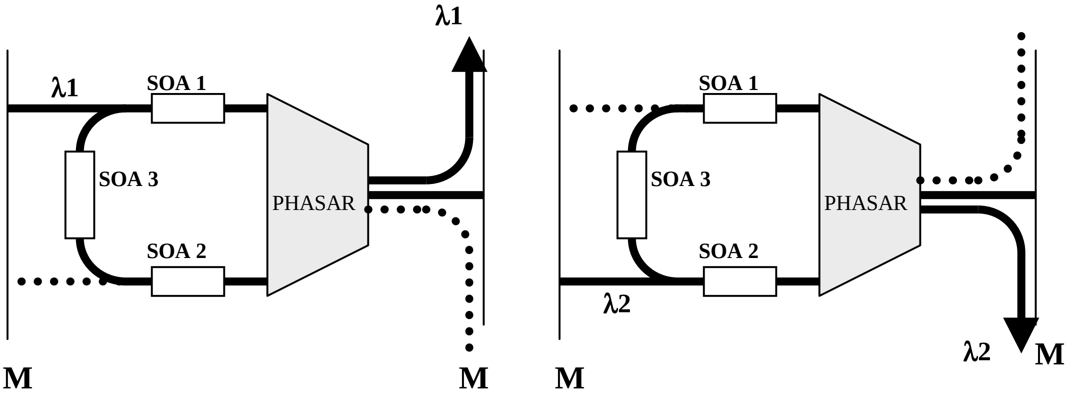

Figure 1a　　　　　　　　　　Figure 1b

Figure 1. *Schematic overview of the optical memory cell based on two coupled cavities in its two stable states, producing output at λ1 (a) or λ2 (b).*

situation in given figure 1a. Note that the waveguide at the right-hand side of the PHASAR that leads to the facet mirror is part of both cavities 1 and 2. In a real mask design all mirrors (M) will be on the same facet. In figure 1b the opposite situation is depicted. To switch the devices between the two states we have looked at injecting a pulse at λ1 or λ2. These pulses can in practice be injected into the common waveguide; the PHASAR directs the light to the correct amplifier. Otherwise the pulses can be injected in the SOA arms directly. Most of the output power of the device is now in two separate waveguides that can be combined, e.g. using a low-loss combiner [3].

To describe this device a rate equation model was set-up in MathCAD. The equations were solved using an adaptive step-size Runge-Kutta solver. The amplifier SOA 3 was modelled very simply by taking a fixed amplification factor for every input. This amplification is taken relatively low (< 5). This will have to be improved. The differential equations used are given below:

$$\frac{\partial \varphi_1}{\partial t} = \varphi 1\left[(N_1 - N0_1)v_g \alpha\Gamma \frac{L_{soa}}{L_{cav1}} - \frac{-\ln(R) + Loss_{cav1}}{\tau_{cav1}}\right] + N_1^2 B\Gamma\beta \frac{L_{soa}}{L_{cav1}} + \Phi 1in(t)$$

$$\frac{\partial \varphi_2}{\partial t} = \varphi 2\left[(N_2 - N0_2)v_g \alpha\Gamma \frac{L_{soa}}{L_{cav2}} - \frac{-\ln(R) + Loss_{cav2}}{\tau_{cav2}}\right] + N_2^2 B\Gamma\beta \frac{L_{soa}}{L_{cav2}} + \Phi 2in(t)$$

$$\frac{\partial N_1}{\partial t} = (N0_1 - N_1)\left[\varphi_1 + \varphi_2\left(\frac{1-R}{1+R}\right)CC\right]v_g\alpha - \frac{N_1}{\tau_{car}} - BN_1^2 - CN_1^3 + W1$$

$$\frac{\partial N_1}{\partial t} = (N0_1 - N_1)\left[\varphi_1 + \varphi_2\left(\frac{1-R}{1+R}\right)CC\right]v_g\alpha - \frac{N_1}{\tau_{car}} - BN_1^2 - CN_1^3 + W1$$

Here $N0_1$ and $N0_2$ are the transparency carrier densities in the amplifier ($1.05*10^{24}m^{-3}$); v_g is the group velocity; α is the gain per carrier; Γ is confinement factor; L_{SOA} is the length of the SOA (0.5mm); L_{cav1}, L_{cav2} are the cavity lengths (3mm taken equal); $Loss_{cav1}$, $Loss_{cav2}$ intra-cavity losses, R is the fraction coupled that stays in the cavity per round trip (0.1); CC is the amplification by the amplifier, τ_{cav1}, τ_{cav2} are the cavity

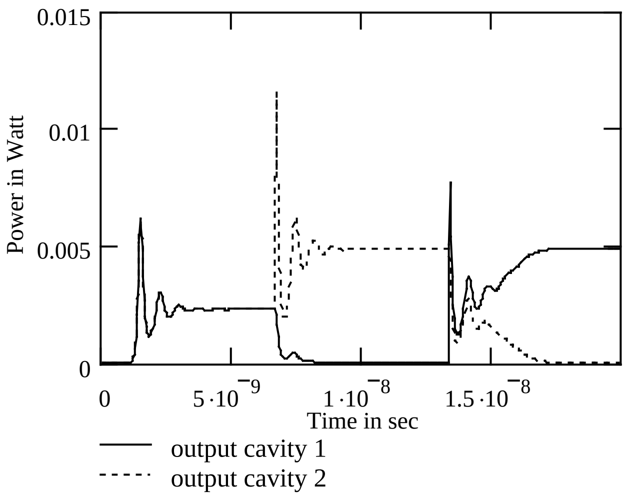

Figure 2. *Output power of the memory system as a function of time with a 50ps set pulse and reset pulse.*

roundtrip times; τ_{car} is the carrier lifetime, B is the bimolecular recombination rate, C is the Auger recombination rate; and *W1* and W2 are the carrier injection rates (e.g. 230mA). For the parameters for the SOAs we used numbers that have shown to give reasonable results in modelling Fabry-Perot test laser structures.

A number of aspects have been determined to be of particular importance. The amplifier coupling the two cavities is essential for the bistability for the sort of parameters that we can practically achieve. The device seems to work best with very fractions of light being coupled out of the cavity through the amplifier. In such situations the required amplification is minimal (typically 1.4 or so). With 50% output coupling amplification factors closer to 5 are required. An example of a simulation is given in figure 2. This shows the power of the two output colours, at the connection point to the amplifier. In the example we have an output coupling from the cavity of about 90% (R=0.1) and CC at 1.4. After the start-up first a λ2 pulse is injected, then 13nsec later a λ1 pulse is injected. These 50ps pulses have an energy of 0.4 pJ. Since the roundtrip time in the cavity is 30ps and the cavity-averaged equations are used this is about the limit for the model. Note that the set/reset pulses can be much shorter than the settling time of the circuit, which is in the order of a few nanoseconds.

Lasers with saturable absorbers

A second option that is looked into for use as an optical memory is a multi-wavelength laser with saturable absorbers. Figure 3 depicts the schematic layout of the system that we have modeled. It consists of a cavity containing a PHASAR in the middle, an SOA in the waveguide at the multiplexed end of the PHASAR and a saturable absorber in each of the two de-multiplexed connections to the PHASAR (ABS 1 and ABS 2). The absorbers are exactly the same as SOA, however they will not be forward biased. By shortcutting the absorber sections or reverse biasing them the recovery lifetime in these absorbers can be reduced in a controlled way. The system has two stable states. The resonator is formed by the facet reflections and all mirrors can be on one facets. The first state is when the laser is operating at λ1, ABS 1 is bleached, and ABS 2 is not. This situation is

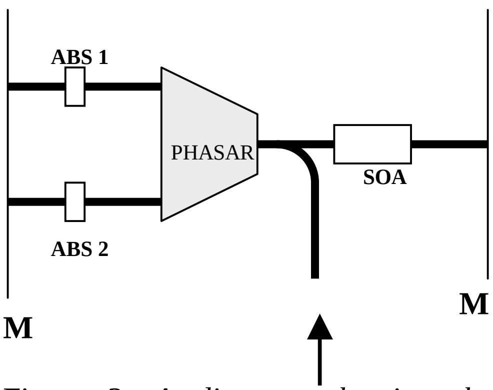

Figure 3. *A diagram showing the memory cell based on a tunable laser with saturable absorbers.*

stable through the mode competition in the SOA since the roundtrip gain at λ1 is higher than that at λ2. The second state is where the laser is operating at λ2. The input for the set-reset pulses can be at the input indicated if the set/reset pulses are with different wavelengths. Pulses can also be injected into the cavities at the facets near ABS 1 and ABS 2. The advantages of this type of memory is that it there is only one SOA and the scheme can in principle be extended to more then two wavelength channels, each with an absorber to make a multi-state memory unit.

The model consists of five differential equations, two for each of the photon densities at the two wavelengths, one for the carrier density in the SOA and two for the carrier densities in the absorber sections. We have no room to present these equations here and thus will present a typical result, in figure 4, demonstrating the bi-stability and switching using optical pulses at the two wavelengths. Figure 4 shows the start of the calculation, the effect of a set and a reset pulse in the circuit. In this simulation we have 200mA through 500µm long SOA and 15µm long absorbers. The carrier lifetime in the absorbers is taken at 1/10 of the 0.6ns carrier lifetime in the SOA. The set and reset pulses are 50ps pulses with an energy of 1pJ. There are a number of features that are notably different from the previous circuits. The settling time of the circuits is approximately 10 times longer while the cavity length (3mm) is the same in both circuits. The output power level in the wavelength that is 'off' is an issue. In the example above the ratio between the 'on' and 'off' wavelength is about 17dB. Reducing the carrier lifetime in the absorbers improves this, but it also increases the energy requirement on the set/reset pulses. The lifetime and the length of the absorbers will have to be optimised. Bringing the laser closer to threshold reduces the requirement on the set and reset pulses but increases the settling time and reduces the contrast again.

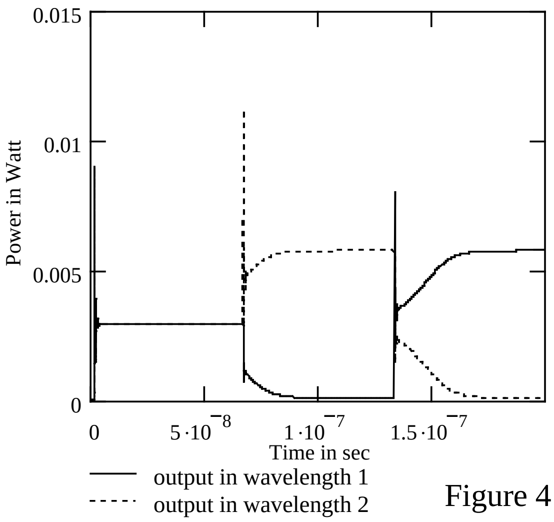

Figure 4

Conclusion

We have designed and set up rate equation models for two types of memory cells. Using these models we can design optical memory devices that can be fabricated using our standard active-passive integration technology.

References

[1] Martin T. Hill, H. de Waardt, G. D. Khoe, and H. J.S. Dorren, ''All Optical Flip-Flop based on Coupled Laser Diodes'', IEEE J. QE, Vol. 37, No. 3, March 2001

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[3] STW Technology Foundation project LossLess Combiner EOE.5440