High Speed, High Switching Contrast Quantum Well Saturable Absorber for 160 Gbit/s Operation

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Abstract: We report on a novel quantum well saturable absorber device whose measured response time of 1.5 psec and contrast of at least 4 dB make it suitable for all-optical extinction ratio enhancement at 160 Gbit/s.

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1. Introduction

Increases in traffic indicate that future transmission networks will need to operate at 160Gbit/s per channel. In such systems ultra high speed regenerators will be required to combat cumulative transmission impairments. Ultra-fast absorption saturation in semi-conductor devices is a promising and cost effective approach to signal regeneration. Relaxation times can be adjusted to less than 1 psec [1,2] and the benefits of quantum well microcavity saturable absorbers have already been reported in a 40 Gbit/s long haul transmission demonstration using a 5 psec relaxation time component [3].

In this paper, we present improved quantum well microcavity saturable absorber devices, the characteristics of which are adequate for all-optical switching operation at repetition rates up to 160 Gbit/s. Due to the dissipative nature of saturable absorber optical switches, the main challenge is to obtain not just a fast response time, but also robustness with respect to the operating power of high repetition rate optical systems.

2. Chip fabrication

The device, shown schematically on Fig. 1(a), is a vertical microcavity used in reflection at normal incidence so as to be polarization independent, with 7 MOCVD-grown InGaAs/InAlAs quantum wells suitably located at the antinodes of intracavity intensity, and irradiated with 11MeV Ni⁺ ions (dose $1 \times 10^{12} \text{cm}^{-2}$) to reduce their carrier lifetime [4]. The bottom mirror is a thin silver film and the top mirror is an InP/InGaAlAs Bragg reflector. To enhance the nonlinear response, the cavity was designed to have a minimum reflectivity close to zero at low intensity (impedance matching) and to be wavelength-matched to the quantum well exciton line. To facilitate heat dissipation, the device was transferred to a silicon wafer by means of In-Au metallic bonding.

3. Device time scales

Due to the very large difference in time scale between the absorption saturation itself and the thermal effects, they can be discussed and evaluated separately.

The time scale for absorption saturation in quantum wells is directly related to the carrier recombination time, which in our case is shortened by the introduction of recombination centers created via ion irradiation. For adequate response to digital optical signals, the absorption saturation will have to process consecutive pulses independently. The carrier recombination time τ must then be shorter than the bit duration $\tau_b = 1/R_b$ where R_b is the bit rate. The speed of our saturable absorber device was measured in a classical pump and probe experiment using 1.2 psec pulses from a passively mode-locked erbium doped fiber laser operating at 1550 nm wavelength. The results show a response time τ of 1.5 psec (see Fig. 1b), which is less than $0.25 \tau_b$ and short enough to work at 160Gbit/s.

On the other hand, the time scale of thermal effects is of the order of microseconds, so that an optically induced, steady state absorber temperature rise can be considered. This may reasonably be assumed to be directly proportional to the average absorbed power. The main effect of the temperature rise is to shift the cavity resonance

towards longer wavelengths. An additional effect is a shift of bandgap with temperature: its importance depends on the relative positions of the cavity and the exciton resonances.

Fig. 1. (a) Device structure, and (b) device response time measured in a pump-probe setup

4. Device modelling

A detailed modelling of the switching characteristics, in the presence of thermal effects, was developed to assess the ability of our device to process ultrahigh bit rate signals. In this model, a steady state analysis of the photoexcited carrier density N_c is performed assuming that $\tau < \tau_b$. The value of N_c depends primarily on the instantaneous value of the incident optical power, but also on other parameters such as the average temperature of the active zone T_{act} . In parallel, T_{act} is calculated from the average absorbed power (which depends on N_c). Hence we perform a self-consistent modelling of the variations of N_c and T_{act} with the parameters characterizing the incident optical signals at a given wavelength λ . In spite of the complexity of these phenomena, the calculations are essentially the solution of a series of steady state equations. Some key features of the modelling are the following: (1) a Fabry-Perot model is used to calculate both the intracavity power resonance behaviour and the spectral dependence of the device reflectance, (2) a microscopic model of the quantum well absorption describes its dependence on λ , N_c and T_{act} , and (3) it includes a phenomenological description of the resonance spectral shift with N_c and T_{act} , based on independently measured data. Finally, (4) the evaluation of the *absorbed power* takes into account the saturable loss due the quantum well absorption (proportional to N_c) and an additional nonsaturable loss, essentially due to the bottom mirror loss (proportional to the intracavity power).

From this model, it is found that the optically induced temperature rise is essentially proportional to the thermal resistance, the signal filling factor, the total volume of the illuminated quantum wells and is inversely proportional to the carrier lifetime τ . The main effect of the optically induced rise of T_{act} is seen to be the wavelength shift of the cavity resonance.

For fixed values of the above quantities and for a fixed signal filling factor, one may therefore consider the evolution of both R_{on} , the device reflectivity when illuminated by an optical ONE, and R_{off} , the device reflectivity when illuminated by an optical ZERO, as a function of incident power. It is seen that, due to absorption saturation, R_{on} is primarily dependent on the signal *peak* power, while R_{off} is essentially dependent on the *average* power.

5. Experimental results

To provide an experimental test of this model, we measured the evolution of the device switching characteristics under high average power input signals. In this setup (of the wavelength-conversion type), a modulated pump beam and a CW probe beam were focused on the device with a fiber-pigtailed high aperture lens providing a focused spot of 5 μm diameter at $1/e^2$ intensity. After spectral filtering and optical amplification, the extinction ratio of the reflected probe signal was measured using a fast photodetector and oscilloscope combination.

The pump signal consists of a repeated digital optical word of duration $N \times T_{bit}$ where N is integer, but can be varied. Each word contains one Return-to-Zero (RZ) optical pulse of FWHM duration τ_p . The filling factor (FF) is defined as the ratio of pulse length to word length or $(\tau_p / N \times T_{bit})$ and can be varied simply by varying N . Since energy is supplied only during the optical pulse, the filling factor also gives the ratio of average power to peak power.

In the experimental work, the pump signal was produced by a 10 Gbit/s RZ optical word generator having $T_{\text{bit}} = 100$ psec and pulse duration $\tau_p = 50$ psec.

Since the cavity resonance was measured to be at 1558 nm, the pump and probe were placed at 1554 nm and 1560 nm respectively.

6. Discussion

The experimental results obtained for 3 values of the filling factor FF, are presented in Fig. 2 (a) and (b) below. It is seen that the contrast increases with the average optical power due to the saturation of the absorption.

It can also be seen that the contrast ($R_{\text{on}}/R_{\text{off}}$), measured for an average optical power of 15 dBm, increases as the filling factor decreases. This arises because R_{on} depends directly on the reflectance of the component which increases with the peak power. On the other hand, R_{off} is seen to decrease as the average power increases. This is essentially due to the heating effect of the optical pump which causes both the cavity and exciton resonances to shift to longer wavelengths with increasing temperature. The good agreement observed between the model and the experimental results serves to validate our modelling of the component.

The measured relaxation time of the device, at 1.5 psec, is short enough to be compatible with operation at 160 Gbit/sec, so that device performance will be essentially bit rate independent up to this rate. The other limiting factor in device performance is that of thermal effects. We have demonstrated, however, that it is possible to have a contrast of 4 dB with a FF of 0.25, despite the thermal effects. Thus we can expect that a 2R (Reamplification + Reshaping) regeneration configuration will allow us to obtain a 4 dB extinction ratio improvement when applied to a 160 Gbit/s optical RZ 50% duty cycle signal which also has a FF of 0.25.

Fig. 2. Theoretical (lines) and experimental (symbols) results for: (a) switching contrast and (b) evolution of R_{on} and R_{off} .

7. Conclusion

In conclusion, we have presented characteristics of improved quantum well microcavity saturable absorber devices. Calculations, which take into account Fabry-Perot microcavity, quantum well, saturable absorption, bottom mirror nonsaturable loss, and a phenomenological description of the resonance shift with carrier density and the active material temperature, have been carried out with a self-consistent method. The calculated results are largely confirmed by preliminary experiments in which the filling factor of the input signal has been varied. With a filling factor compatible with a bit-rate of 160Gb/s, both calculation and experiment show that the improved saturable absorber device should be capable of handling 2R regeneration, with a sufficiently large switching contrast.

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