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Full Length Article

Simulations of an all-optical flip-flop with a reset pulse frequency exceeding operating frequency

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ABSTRACT

An all-optical flip-flop based on a nonlinear multi-section DFB semiconductor laser structure is proposed. Holding beam is not required for device's operation. A section of the DFB structure is detuned to prevent lasing in the "OFF" state, and it is accompanied with a negative nonlinear coefficient that is due to partial absorption of photons at Urbach tail. At a high light intensity in the structure the nonlinear coefficient reduces the detuning, and the device is in lasing state; "ON" state. The device is reset by an optical pulse at a shorter wavelength through cross gain modulation. The reset pulse is absorbed in a middle section in the device before reaching the detuned nonlinear section. The switching times between the states are in nanoseconds time scale.

1. Introduction

All optical Internet requires all optical devices to process optical data directly (without conversion to electrical signal) in the optical domain. Particularly, all-optical flip-flops have roles as all optical memory elements, and these memory elements could be used in all optical data routing [1]. The all-optical flip-flop could be used for other applications such as optical shift register, optical random access memory and other applications [2]. Several schemes/devices are suggested for all-optical flip-flop devices. In [3], a device that is based on two coupled laser diode is presented. A device that is constructed from ring laser is presented in [4]. A device with two states of a clockwise and an anti-clockwise laser mode is introduced in [5]. Devices that are based on a semiconductor distributed feedback (DFB) laser, and on vertical cavity semiconductor optical amplifier (VCSOA) are shown in [6] and [7] respectively. All these devices require a holding beam or show output power in both states of the flip flop. Devices that have bistable optical output and do not require a holding beam are discussed in [8,9]. These devices have a saturable absorber in the laser cavity which has large optical loss at low light intensity in the laser cavity, and optical loss is reduced at high optical power intensity in the cavity.

In [10], a chirped DFB laser structure that behaves as an all-optical flip-flop is simulated. The flip-flop has a bi-stable output optical power behavior. The operation of the device does not require a holding beam. The chirped grating is accompanied by a linearly increasing negative nonlinear coefficient that is due to partial absorption of photons at the Urbach tail (The absorbed photons produce electron-hole pairs density that reduce the refractive index close to the band-gap energy). In the "OFF" state the chirp prevents constructive feedback from the grating and lasing does not occur. At high light intensity,

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the chirp is reduced due to negative nonlinearity, and the laser mode builds up. The device is switched “OFF” by cross gain modulation. An optical pulse of a wavelength longer than the operating wavelength reduces the gain of the active layer, and in the same time does not produce much change in the refractive index (lower absorption coefficient at a longer wavelength).

In this work, a new design for an all-optical flip-flop is simulated. Instead of the chirped grating accompanied with a linear increasing negative nonlinear coefficient, a part of the wave-guiding grating of the suggested device is detuned from the rest of the grating. The detuned part has a slightly higher refractive index than the rest of the grating and has a negative nonlinear coefficient. The negative nonlinear coefficient is due to partial absorption of photons at the Urbach tail. The structure investigated in this work is easier to fabricate than the structure mentioned in [10] because only one nonlinear section is needed to achieve optical bistability in the laser device. The switch OFF (“Reset”) mechanism is done by cross gain modulation (XGM), and a “Reset” pulse at a wavelength shorter than the wavelength of the “Set” pulse is used. The “Reset” pulse has a higher frequency (shorter wavelength) than the “Set” pulse and the operating frequency, which produces more design flexibility. This is in contrast to the device in [10], where the the “Reset” pulse has to be at a lower frequency than the operating frequency. In the next section the device schematic is presented and the flip-flop design is discussed.

2. Device schematic and description

The suggested device consists of a nonlinear DFB laser structure. The refractive index distribution along the wave-guiding layer of the device is shown in Fig. 1. The grating

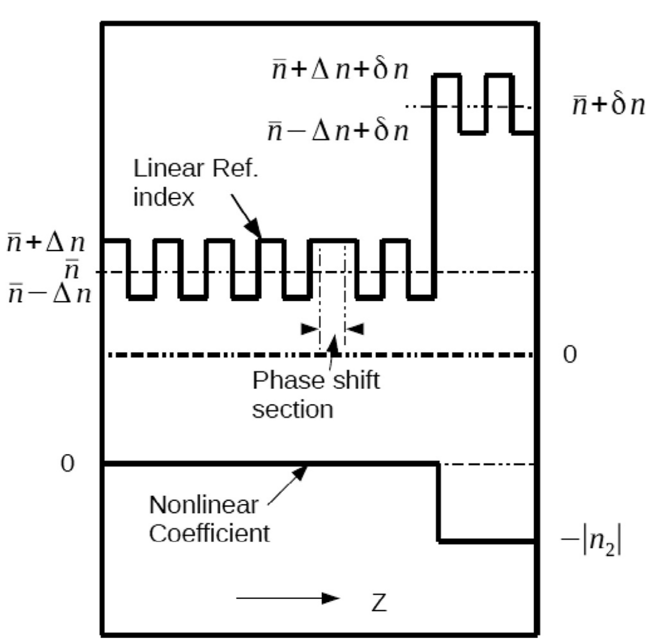

Fig. 1 – Linear refractive index and nonlinear coefficient distribution.

period is adjusted as $2\bar{n}d = \lambda_G$, where $\bar{n}$ is the average refractive index along the grating, d is the grating period, λ_G is the wavelength at the center of the reflection band of the grating. The device has a phase shift section in the middle of the grating. The optical gain is provided by electrical current injected into the active layer along the wave-guiding layer. The negative nonlinear coefficient is due to direct absorption of photons at the Urbach tail at a photon energy slightly less than the semiconductor band-gap energy in the nonlinear section. The loss coefficient at the Urbach tail is expressed as: $\alpha(\omega) = \alpha_0 \times exp((\hbar\omega - \hbar\omega_g)/E_0)$ [11,12], $\hbar\omega_g = E_g$ is the band gap energy, $\hbar$ is the Plank’s constant (The energies are expressed in electron volt). The absorbed photons produce electron-hole pairs that reduce the refractive index at a photon energy slightly less than the semiconductor band-gap. At low optical power intensity in the structure, the detuned part of the wave-guiding layer reduces the available optical feedback to the laser mode, and the laser mode does not build up. To set the flip-flop “ON”, an optical pulse of wavelength $\lambda = \lambda_1$ is injected, at $z = 0$, where $\lambda_1 = \lambda_G$. The semiconductor band gap energy E_g in the nonlinear section is adjusted such that the photons energies at $\lambda = \lambda_1$ is slightly less than E_g. Fig. 2 shows the gain spectrum of the device [13], the “Set” and “Reset” pulses frequencies (wavelengths), and the optical loss at Urbach tail. The injected “Set” pulse induces electron-hole pair densities in the nonlinear section and reduces its refractive index and its detuning; hence it provides extra optical feedback to photons of wavelength around $\lambda = \lambda_1$, the optical mode builds up and provides optical power (photons) that produce electron-hole pairs in the nonlinear section and maintain the reduction in the detuning in that section.

To reset the flip-flop, an optical pulse at $\lambda = \lambda_2$ is injected at $z = 0$. In this work we choose $\lambda_2 < \lambda_1$, which means that the reset pulse will be absorbed in the nonlinear section and may prevent the flip-flop from switching “OFF” properly. At $L/2 < z < 3L/4$ along the wave-guiding layer, the band-gap of the wave-guiding layer is altered to provide large absorption to photons of wavelength $\lambda = \lambda_2$ (Fig. 3). In Section “1”, the band gap energy is higher than “Set/Reset” pulse photons energies. In section “2”, the “Reset” pulse will be absorbed because the band gap energy is lower than the “Reset” pulse photon energy. The “Reset” pulse energy is totally absorbed in section “2” before it reaches section “3”. Section “3” is the detuned

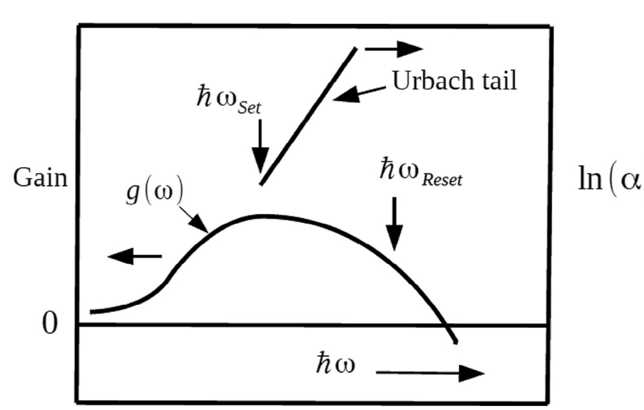

Fig. 2 – Gain spectrum, Urbach tail loss and “Set/Reset” pulses frequencies (wavelengths).