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Structure design and performance simulation on monolithic integrated chaotic-optical transmitter with photonic crystal waveguide in external cavity

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ABSTRACT

A novel monolithic integrated chaotic-optical transmitter structure is proposed in this paper. It consists of a distributed feedback laser, a semiconductor optical amplifier, a passive waveguide, and a photonic crystal waveguide. The length of external cavity is shorten to 1.125 mm by the slow light effect in photonic crystal waveguide. The performance of the integrated chaotic-optical transmitter is simulated. A series of dynamic states transiting from steady state, period state, and finally to chaotic laser is obtained. The size and power consumption of the chaotic-optical transmitter are both reduced by introduction of photonic crystal waveguide.

1. Introduction

Chaotic laser has been widely used in many areas, such as secure optical communications and random number generation, etc [1–3]. Common chaotic laser transmitters are based on a couple of optical bulk devices, which are bulky, complicated, and unstable. In the recent five years, photonic integrated chips subject to optical feedback are proposed, designed and fabricated [4,5]. The chips, whose time delay is provided by optical waveguides, have a compact structure and strong output stability. Typical structures include linear feedback type [4] and ring feedback type [5]. The structure of the former is simple, but the length of the optical waveguide is about 1 cm, which makes the size of the chip must be several centimeters. The ring type can reduce the size, but because of the large internal loss in the bend waveguides, the chip has to introduce more semiconductor optical amplifiers, which increase the power consumption of the chip. The design of photonic integrated chips with both more compact and lower power consumption is important.

In this paper, a novel structure of monolithic integrated chaotic-optical transmitter is proposed. It consists of a distributed feedback laser, a semiconductor optical amplifier, a passive connecting waveguide, and a photonic crystal waveguide. Time delay for chaotic laser generation is provided by the slow light effect for photonic crystal waveguide. The advantage of photonic crystal waveguide is that it can simultaneously reduce the size and power consumption of the chip.

This paper is organized as follows. In Section 2, the structure and the design procedures of monolithic integrated chaotic laser are described. In Section 3, the performance of the transmitter is simulated and analyzed. The conclusion of this paper is provided in Section 4.

2. Structure design of monolithic integrated chaotic-optical transmitter

The structure of monolithic integrated chaotic-optical transmitter with a photonic crystal waveguide is shown in Fig. 1. It consists of four sections, a distributed feedback (DFB) laser, a semiconductor optical amplifier (SOA), a passive waveguide and a photonic crystal waveguide. The lengths of the DFB laser, SOA, and passive waveguide are 500 μm, 200 μm, and 5 μm, respectively. The width and height of the ridge waveguide are 2 μm, and 1.5 μm, respectively. The cross section of the active device region (DFB, SOA) and the passive device region (connecting waveguide) is shown in Fig. 2. The reflective film is plated at the end of the photonic crystal waveguide, which provides the optical feedback for the DFB laser. The length of the photonic crystal waveguide is determined by the time delay for chaotic laser generation and the speed of the slow light mode.

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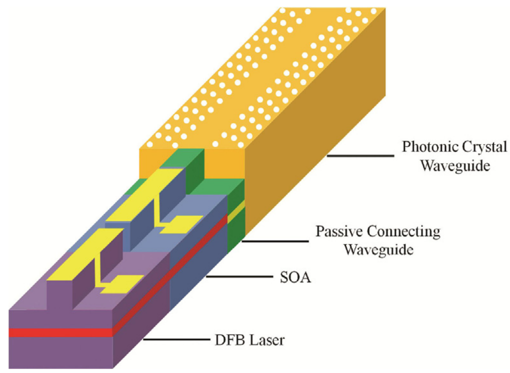

Fig. 1. Structure of monolithic integrated chaotic-optical transmitter.

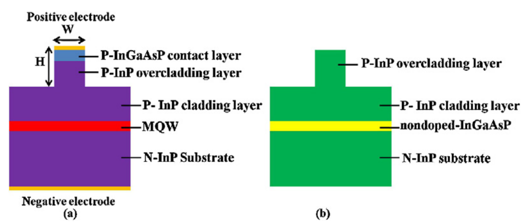

Fig. 2. Cross section of (a) active device section, (b) passive device section.

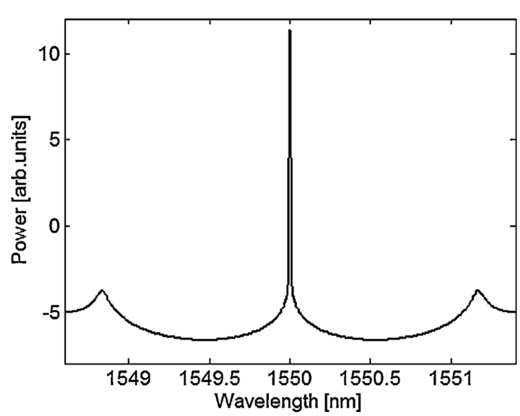

Fig. 3. Calculated lasing spectrum of DFB laser.

The design of DFB laser is accomplished by transfer-matrix-method (TMM) [6], and the parameters used in the simulation for DFB laser is listed in Table 1. The calculated lasing optical spectrum of the DFB laser is shown in Fig. 3. It can be seen from Fig. 3 that the designed laser can operate in a single longitudinal mode within 1 nm in the vicinity of the central wavelength of 1550 nm.

Table 1
Main parameters used in simulation on DFB laser.

Parameters	Values
Cavity length	500 μm
Active layer thickness	0.12 μm
Waveguide loss	40 cm^{-1}
Differential gain	2.7×10^{-16} cm^2
Optical field confinement factor	0.35
Carrier lifetime	4 ns
Linewidth enhancement factor	5.4
Group index	3.7

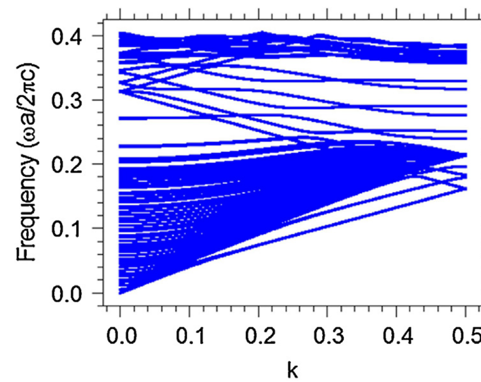

Fig. 4. Dispersion relationship of W3 type photonic crystal waveguide, $r/a = 0.36$, where k is the wave vector.

The model of semiconductor laser subject to coherent optical feedback can be described by the classic Lang-Kobayashi delayed differential equations [7]

$$\begin{aligned}
\frac{dE(t)}{dt} &= \frac{1}{2}\left[G_N(N(t)-N_0)-\frac{1}{\tau_p}\right]E(t)+\kappa E(t-\tau)\cos\Theta(t)\\
\frac{d\Phi(t)}{dt} &= \frac{\alpha}{2}\left[G_N(N(t)-N_0)-\frac{1}{\tau_p}\right]-\kappa\frac{E(t-\tau)}{E(t)}\sin\Theta(t)\\
\frac{dN(t)}{dt} &= J-\frac{N(t)}{\tau_s}-G_N(N(t)-N_0)E^2(t)\\
\Theta(t) &= \omega\tau+\Phi(t)-\Phi(t-\tau)
\end{aligned} \quad (1)$$

where τ is the time delay, κ is the feedback strength, G_N is the gain coefficient, $N(t)$ is the carrier density, N_0 is the carrier density at transparency, τ_p is the photon lifetime, ω is the angular frequency of laser, α is the linewidth enhancement, J is the normalized injection current, and τ_s is carrier lifetime. It can be found by numerical simulation that, in order to reduce the size of the chip, the minimal time delay for chaotic laser generation can be 75 ps. For linear type photonic integrated chips, to achieve that time delay, the length of external cavity is 1.125 cm in vacuum, and 3.75 mm in traditional optical waveguide. Nevertheless, if the time delay is achieved by the slow light effect of photonic crystal waveguide, the length of external cavity can be significantly reduced.

Common photonic crystal waveguides include W1 type and W3 type [8]. W1 type waveguide is narrow in width, which requires a long tapered connecting waveguide when integrated with ridge waveguide. The coupling efficiency is low, and there will be additional propagation loss. Moreover, W1 type waveguides are very sensitive to fabrication imperfections, disorder for instance, that induces large propagation loss in slow light region. In contrary, W3 type waveguides are wider, which means a higher coupling efficiency and a lower propagation loss [9]. So a W3 type waveguide is chosen in this paper. The dispersion relationship calculated by the plane wave expansion (PWE) method [10] is shown in Fig. 4. It is assumed that all the devices operating in TE mode.

The mini-stopband in W3 type photonic crystal waveguide is shown in Fig. 5. It can be seen that the fundamental mode in the vicinity of mini-stopband is flat, where is the slow light region of W3 type photonic crystal waveguide. The group velocity can be calculated directly from the dispersion relation

$$v_g = \frac{d\omega}{dk} = \frac{c}{n_g} \quad (2)$$

where ω is the angular frequency, k is the wave vector, c is the speed of light in vacuum, and n_g is the group index. The calculated group velocity as the function of normalized frequency near mini-stopband is shown in Fig. 6.