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Monolithically integrated grating and deflector structure for wavelength filtering

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Abstract: A simple integrated deflector and grating structure is proposed for a wavelength filtering. The deflector is composed of a channel waveguide and a slab waveguide with a tapered gap between them to generate a Gaussian light beam in the slab waveguide. The echelle type grating is formed at the end of the slab waveguide. The distance between the grating and the deflector is 100–200 μm. The device is designed using diffraction theory. The filter response is verified using bi-directional BPM. Tuning range of 25 nm for 5.4×10^{-3} refractive index change and filter passband width of 15 nm were attained by a 350 μm long device at 1500 nm wavelength.

Keywords: deflector, grating, tunable wavelength filter

Classification: Photonics devices, circuits, and systems

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1 Introduction

A tunable wavelength laser diode (LD) is a valuable device in constructing an optical communication systems using wavelength demultiplexing. The device is also useful in sensor systems. Many structures have been proposed for tunable LD using myriad types of wavelength selecting schemes. An element structure using a combination of a deflector and grating has a potential of achieving a mode-hop-free wavelength tuning [1, 2]. Conventional device employed an external cavity structure in which the grating is used as an external wavelength selective mirror. A long external cavity is not suitable for achieving a mode-hop-free operation. Recently, an external cavity device with deflector integrated into LD chip was reported [3].

In this report we propose a design for the filtering element [4] using a simple deflector structure. The distance between the grating and the deflector can be reduced to 100 μm enabling the integration of the deflector and the grating [5].

2 Device structure

The device structure is shown in Fig. 1. The device is composed of a grating for wavelength selective diffraction and a deflector to control the angle of the light beam impinged on the grating.

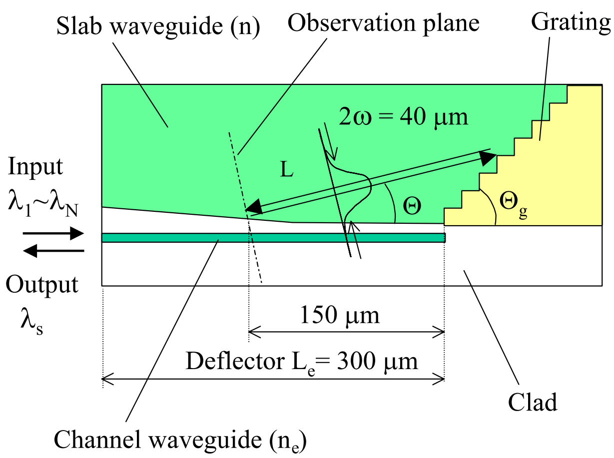

Fig. 1. Device structure

The deflector is composed of a channel and a slab waveguides placed next to each other with a gap between them. The deflector structure is fabricated with the same process as that for the directional coupler switch reported using compound semiconductor material. The light propagated in the channel waveguide is coupled out into the slab waveguide. Changing the refractive index of the channel waveguide controls the light beam direction in the slab waveguide.

A grating is placed at the end of the slab wavguide to diffract back the light propagated in the slab waveguide. The direction of the backward propagating light generated by the grating is a function of the wavelength and

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the incident angle. The backward propagating light in the slab waveguide is coupled back into the channel waveguide at the deflector. The coupling efficiency depends on the angle difference between the forward and backward propagating light beam. The coupling efficiency is high when the backward light beam that aligns with the forward light is generated. The light-beam-aligning wavelength can be changed by controlling the grating incident light beam angle with the deflector. A desired wavelength light is ejected as a reflected light at the output port.

We can eliminate the lens to shorten the device by using a deflector structure that produces a light with Gaussian beam field distribution [4]. This design can reduce the distance between the grating and the deflector to a length much smaller than the Rayleigh range.

3 Device design

First we analyze the structure for mode-hop-free condition to select the grating angle. The wavelength tuning due to light beam angle change $\Delta\Theta$ is given by

$$\Delta\lambda/\lambda = \tan(\Theta_g - \Theta)\Delta\Theta. \quad (1)$$

where λ is the wavelength, Θ_g and Θ are the grating and light beam angles respectively. Note that geometry is slightly different from the Littrow dispersion calculation configuration that input and output angle is changed simultaneously. The distance L between the deflector and the grating along the center of the light beam changes by $\Delta\Theta$. The standing wave condition for the cavity incorporating the deflector-grating structure becomes, $k_0\ (nL + n_e L_e + n_c L_c) = q\pi$, where k_0 is the light wave number and q is an integer. L_e and L_c are the lengths of deflector (electrode) and additional sections respectively. The refractive indices of the slab waveguide, electrode and additional sections are denoted as n, n_e and n_c respectively. From these equations, the mod-hop-free condition is derived. If $\Theta_g - \Theta = \pi/4$ the mode-hop-free condition becomes independent of nL. In this report we design the device around this angle. Mode hopping was suppressed by optimized design with slightly lower angle. Controlling the refractive index at the additional section compensates for the small deviation from the mode-hop-free condition due to angle change.

From Eq. 1 it is known that the diffraction angle changes with the wavelength as $\Delta\Theta/\Delta\lambda = 1/[\lambda\tan(\Theta_g - \Theta)]$. For an example, $\Delta\Theta/\Delta\lambda = 1.1 \times 10^{-3}$ rad/nm for 1550 nm center wavelength when $\Theta_g - \Theta = 0.5$ rad is used. Equation 1 shows that the wavelength tuning efficiency becomes large when $\Theta_g - \Theta$ approaches $\pi/2$.

The propagation angle change of the light beam generated by the deflector is given by

$$\Delta\Theta = -(\Delta n_e/n_e)/\tan\Theta. \quad (2)$$

The beam deflection for given refractive index change Δn_e becomes larger when angle Θ approaches 0. To generate a Gaussian beam in the slab waveg-

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uide, the gap between the channel and slab waveguides should be tapered as in Ref. 4.

For the evaluation of the device design we used a method based on diffraction theory. The incident light on the grating was assumed to be a Gaussian beam. The beam waist position was located at the deflector or the grating. The difference in characteristics between two configurations is small when the distance between the deflector and the grating is shorter than the Rayleigh range $L_r = \pi\omega_0{}^2 n/\lambda$. Locating the beam waist at the deflector results in a larger width mismatch between forward and backward lights at a longer distance. The waist size ω_0 was varied from 5 to 40 μm. The grating total width was wide enough to cover the Gaussian incident beam. The grating groove period was 0.523 μm. Light field reflected at each grating groove are summed to obtain a diffracted light field on an observation plane normal to the center axis of the incident light beam. The observation plane was placed at the deflector position. A diffracted light similar to the Gaussian beam was obtained at the observation plane when the grating-deflector distance was longer than about 4% of the Rayleigh range. The grating step height (0.22 μm) is small enough to attain wide diffraction angle to facilitate interference between lights diffracted by each step. The propagation angle of the diffracted light beam was nearly equal to that calculated by Eq. 1.

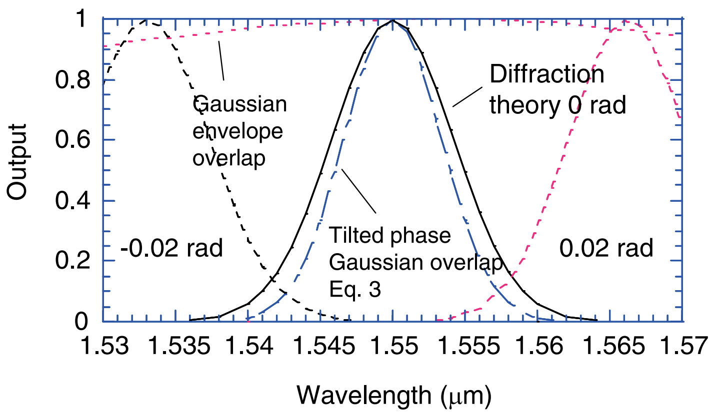

Fig. 2. Calculated filter response.

The wavelength response is calculated by an overlap integral of the Gaussian beam generated by the deflector and the light beam generated by the grating at the deflector position. If both light beams are assumed to be Gaussian beams having the same width, the output is given by

$$\eta = \exp[-(\Delta\Theta L/\omega)^2]\exp[-(\pi\Delta\Theta\omega n/\lambda)^2] \qquad (3)$$

where ω is the half width of the Gaussian beam at the deflector position. The beam waist position is assumed to be at the deflector. The first exponential term is the beam center displacement effect and the second term is due to the mismatch of the inclined light phase. In a device with distance L of several-hundred-micron length, the effect of the beam center displacement is small. The filter response is mainly governed by the second term in Eq. 3.

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The wider the light beam becomes narrower the filter wavelength passband width. The angle deviation is given by $\Delta\Theta = (d\Theta/d\lambda)_L - (d\Theta/d\lambda)_{Eq.\,1}$ where $(d\Theta/d\lambda)_L$ is the dispersion calculated by the Littrow configuration.

Calculated output is shown in Fig. 2. The output given by envelope overlap (corresponding to the first exponential term in Eq. 3) and the second (tilted Gaussian) exponential term in Eq. 3 are shown. The wavelength tuning calculation results obtained by diffraction theory are also shown in Fig. 2. The beam waist half width is 20 μm, and the grating to deflector distance is L=200 μm. The refractive index is 3.4. A large refractive index is advantageous in achieving a narrow filter transmission wavelength width as can be noticed from Eq. 3. We used the angle change rate of $\Delta\Theta/\Delta\lambda = 1.1 \times 10^{-3}$ rad/nm which is derived from the simulation. It can be seen in Fig. 2 that the phase effect (tilted Gaussian) narrows the filter response. The output calculated by Eq. 3 agrees reasonably well with the result obtained by the diffraction theory.

A 14 nm filter transmission full width at half maximum is obtained. A 40 nm tuning range is achieved by ± 0.02 rad light beam steering. The length L could be made short as 100 μm with no degradation of the performance.

4 Bi-directional BPM simulations

To verify the design described in section 3, we used bi-directional BPM [6] to simulate the device performance including those of the deflector. The total deflector length is 300 μm and the deflector to grating distance is 150 μm. The light beam half width is 20 μm. The refractive index of the slab waveguide was 0.01 higher than the channel waveguide. The grating step width and height of 0.4 μm are selected to minimize the digitizing effect due to the calculation step and mesh size. The grating has 200 grooves. The grating and light beam angles were $\Theta_g = \pi/4$ and $\Theta = 0.08$ rad respectively. The center wavelength is around 1490 nm in accordance with the grating step width. The channel waveguide width is 2 μm and the refractive index difference is 0.015. The minimum gap between the slab and channel waveguide is 0.4 μm in the constant gap section extending 50 μm before the grating. The maximum gap at the start of the deflector is 1.6 μm where the coupling of the light to the

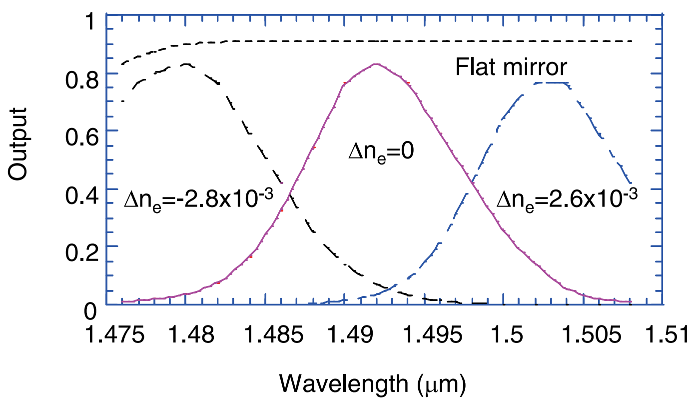

Fig. 3. Bi-directional BPM simulation.

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slab waveguide begins. The gap is narrowed as an arc from input side to the constant gap section of the deflector to generate a Gaussian light beam. The refractive index change Δn_e of 2.6×10^{-3} and -2.8×10^{-3} were used for the light beam deflection at the deflector. The refractive index change of this range is readily obtained by compound semiconductor modulator structure using carrier injection or electro-optic effect.

The results are shown in Fig. 3. The output is the fraction of the device output light power normalized against the plane wave power reflectivity of an infinitely wide mirror, which refractive index is similar to that constituting the grating. To evaluate the wavelength dependence of the deflector, a flat mirror was used, instead of grating, to reflect the light beam from the deflector and the result is also shown in Fig. 3. The deflector shows little wavelength dependence.

The wavelength tuning range of 25 nm is achieved with refractive index change of 5.4×10^{-3}. The tuning range is given by $\Delta\lambda/\lambda = A\ \Delta n_e/n_e$ where A is the tuning enhancement factor. From Eqs. 1 and 2 $A = \tan(\Theta_g - \Theta)/\tan\Theta$. The enhancement factor of A=10 was obtained in the simulation. The approximate filter transmission 1/e half-width $\Delta\lambda_w$ is derived using Eq. 3, $\omega = (L_e/2)\sin\Theta$ and considering the Littrow configuration as in Eq. 4.

$$\Delta\lambda_w/\lambda = A\lambda/(\pi n L_e \cos\Theta). \tag{4}$$

The simulation results agree with the design analysis in section 3.

5 Conclusion

We have described a simple deflector and grating structure to integrate both elements for tunable wavelength filtering. The deflector is composed of a channel waveguide and a slab waveguide with the gap between them tapered to generate a Gaussian light beam. A distance of 100–200 μm between the grating and the deflector is attained for device miniaturization. The device was designed using diffraction theory and the filter response was verified using bi-directional BPM. The filtering function is approximately described by overlap integral of the Gaussian light beams with those axis tilted against each other. Tuning range of 25 nm for 5.4×10^{-3} refractive index change and filter passband width of 15 nm were attained by a 350 μm long device.

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