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Analysis of Coherent Coupling in High-Mesa Directional Coupler

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Abstract We proposed a matrix method to calculate the effect of the coherent coupling in a high-mesa directional coupler. The analyzed results revealed that a small periodic oscillation of loss of the transmitted light depending on a coupler length occurs due to the coherent coupling.

1. Introduction

Directional couplers are widely used for optical waveguide devices. Propagation loss in the directional couplers needs to be reduced as much as possible. As the origin of loss in a waveguide, in addition to scattering and absorption losses, we should consider the interference of leaky modes propagating in a cladding layer with guided modes in a core layer in some cases. This interference between the leaky and guided modes is called "coherent coupling" [1,2]. It may have more than a few effect on the performance of directional couplers, however, the coherent coupling in a directional coupler has never been investigated so far.

In this paper, first we report on the observation of the cladding mode in semiconductor high-mesa waveguides. Next we propose an analyzing technique based on a matrix method for the coherent coupling on coupling loss and coupling efficiency in a directional coupler.

2. Observation of Cladding Mode in Semiconductor Waveguides

To confirm the presence of the cladding mode propagating in a cladding layer, we measured the transmission characteristics of a semiconductor waveguide microring device. The layered structure is the same as that in Ref. [3]. The core layer was composed of an InGaAs/InAlAs multiple quantum well (MQW) structure. It has a pin diode structure and by applying reverse bias to the diode, the electric field is applied to the core layer. The round-trip length of each microring resonator is 220 μm, which corresponds to the free spectral range (FSR) of 2.84 nm.

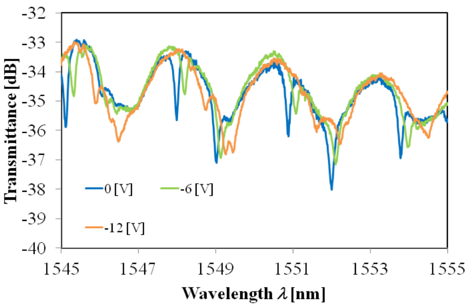

Fig. 1 Spectra of the light transmitted from the input port to the through port under the reverse biases applied to the microring resonator.

Figure 1 shows the spectra of the light transmitted from the input port to the through port under the reverse biases applied to the microring resonator. The sharp dips are due to the resonance of the guided mode in the core layer of the microring resonator. The resonant wavelength of the microring resonator is shifted to a longer wavelength due to the quantum confined Stark effect (QCSE) of the MQW. In addition, the periodic sinusoidal ripple with the FSR of 2.62 nm was also observed, and the peak wavelengths do not change even when the reverse bias was applied to the microring. Assuming that the propagation constant of the upper cladding mode is expressed as β_{clad} (=$2\pi n_{\mathrm{eq}}^{\mathrm{clad}}/\lambda$) and the ripple is caused by the interference between the guided and cladding modes, the equivalent refractive $n_{\mathrm{eq}}^{\mathrm{clad}}$ and β_{clad} are calculated to be approximately 2.97 and 12.04 rad/μm, respectively.

3. General Formulae of Matrix Method for Analysis of Coherent Coupling in Directional Coupler

We propose a matrix method for a directional coupler to calculate the effect of the coherent coupling using the model in Fig. 2. The optical field incident on the WG#1, E_{i1}, is expanded into the even mode E_{e}, odd mode E_{o}, and cladding mode E_{clad} at the input end,

$$E_{i1} = c_{1\mathrm{e}}E_{\mathrm{e}} + c_{1\mathrm{o}}E_{\mathrm{o}} + c_{1\mathrm{clad}}E_{\mathrm{clad}}\,, \qquad (1)$$

where $c_{1\mathrm{e}}$, $c_{1\mathrm{o}}$ and $c_{1\mathrm{clad}}$ are the mode expansion coefficients. The optical field incident on the WG#2 and the radiation field incident on the coupler can be written in a matrix formulation given by

$$\begin{bmatrix} E_{\mathrm{i1}} \\ E_{\mathrm{i2}} \\ E_{\mathrm{ir}} \end{bmatrix} = \mathbf{C}\begin{bmatrix} E_{\mathrm{e}} \\ E_{\mathrm{o}} \\ E_{\mathrm{clad}} \end{bmatrix} = \begin{bmatrix} c_{1\mathrm{e}} & c_{1\mathrm{o}} & c_{1\,\mathrm{clad}} \\ c_{2\mathrm{e}} & c_{2\mathrm{o}} & c_{2\,\mathrm{clad}} \\ c_{\mathrm{re}} & c_{\mathrm{ro}} & c_{\mathrm{r\,clad}} \end{bmatrix}\begin{bmatrix} E_{\mathrm{e}} \\ E_{\mathrm{o}} \\ E_{\mathrm{clad}} \end{bmatrix}, \qquad (2)$$

where **C** is the mode expansion matrix.

Since E_{e}, E_{o}, and E_{clad} are orthogonal to each other, they are guided independently in the coupler with the propagation constants β_{e}, β_{o}, and β_{clad}, respectively. At the output end, the optical fields E_{o1} from WG#1, E_{o2} from WG#2, and E_{or} radiated to free space are expressed in terms of E_{e},

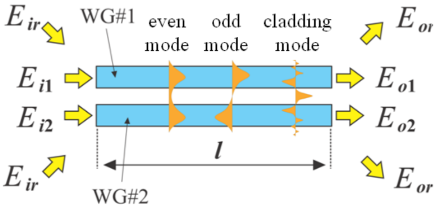

Fig. 2 Calculation model for a matrix method to calculate the effect of the coherent coupling a directional coupler.

E_o, and E_{clad} by a matrix formulation similar to eq.(2). Therefore, the optical fields E_{o1}, E_{o2}, and E_{or} at the output end are related to the fields E_{i1}, E_{i2}, and E_{ir} at the input end by

$$\begin{bmatrix} E_e \\ E_o \\ E_{clad} \end{bmatrix} = \boldsymbol{C} \begin{bmatrix} e^{-j\beta_e l} & 0 & 0 \\ 0 & e^{-j\beta_o l} & 0 \\ 0 & 0 & e^{-j\beta_{clad} l} \end{bmatrix} \boldsymbol{C}^{-1} \begin{bmatrix} E_{i1} \\ E_{i2} \\ E_{ir} \end{bmatrix}, \tag{3}$$

where l is the coupler length. From eq.(3), we obtain

$$\left|E_{or}\right|^2 = \left|c_{1e}c_{re}e^{-j\beta_e l} + c_{1o}c_{ro}e^{-j\beta_o l} + c_{1\,clad}c_{r\,clad}e^{-j\beta_{clad} l}\right|^2. \tag{4}$$

According to the power conservation law, the output power of radiation mode can be written as

$$\begin{aligned} \left|E_{or}\right|^2 &= 1 - \left(\left|E_{o1}\right|^2 + \left|E_{o2}\right|^2\right) = 1 - 2\left(c_{1e}^4 + c_{1o}^4 + c_{1\,clad}^4\right), \\ &\quad - 4c_{1e}^2 c_{1\,clad}^2 \cos\left[\left(\beta_{clad} - \beta_e\right)l\right] \end{aligned} \tag{5}$$

Comparing eq.(5) with eq.(4), we can derive

$$c_{ro} = 0\,. \tag{6}$$

Therefore, eq.(4) is rewritten as

$$\left|E_{or}\right|^2 = \left|c_{1e}c_{re}e^{-j\beta_e l} + c_{1\,clad}c_{r\,clad}e^{-j\beta_{clad} l}\right|^2. \tag{7}$$

Eq. (7) implies that the radiation loss of the coupler depends on the difference of propagation constants between even and cladding modes and the odd mode does not affect the loss.

According to eq.(5), the period of the coupling loss L_c is determined by

$$L_c = 2\pi/(\beta_e - \beta_{clad}), \tag{8}$$

Since β_e and L_c can be obtained by a mode solver and a simulator such as 3D- finite-difference time-domain method (FDTD), respectively, β_{clad} can be evaluated by

$$\beta_{clad} = (\beta_e L_c - 2\pi)/L_c\,. \tag{9}$$

4. Analysis of Semiconductor Directional Coupler Using Matrix Method

We apply the matrix method discussed in §3 to a practical model of a semiconductor directional coupler with a shallow gap [3]. Figure 3 shows the field distribution of light in the directional coupler with a coupler length l = 86.5μm simulated by 3D-FDTD method. The light beam is incident on the input port 1 of the WG#1 and propagates in the coupler with meandering due to the coherent coupling. The coupling loss depends on the coupler length as shown in Fig. 4. The oscillation of coupling has a single periodicity with respect to the propagation distance. This means that a group of radiation modes which causes the interference is regarded as a cladding mode, and can be expressed as a single propagation constant. Since there are two boundary surfaces between the core and cladding layers, the MQW core layer may act as the interference cladding as in the case of the antiresonant reflecting optical waveguide (ARROW) [4], and a leaky mode can propagate in the upper cladding with low loss.

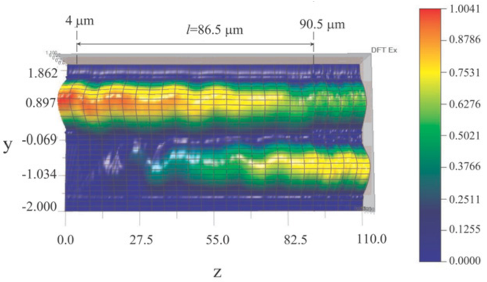

Fig. 3 Field distribution of light in the directional coupler with a coupler length l = 86.5μm simulated by 3D-FDTD.

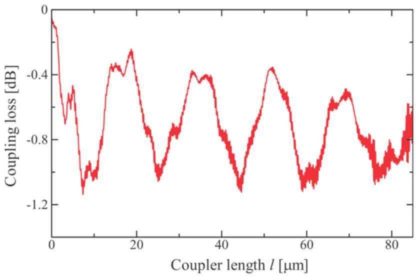

Fig. 4 Coupling loss depends on the coupler length calculated by 3D-FDTD.

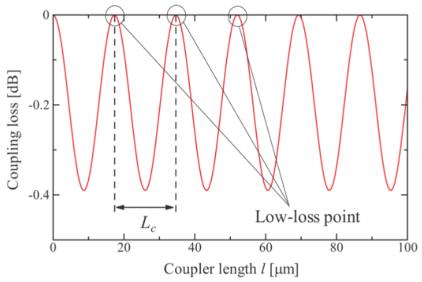

Fig. 5 Theoretical dependences of the coupling loss on the coupler length l calculated using the proposed matrix method.

Figure 5 shows the calculated theoretical dependences of the coupling loss on the coupler length l by using the proposed matrix method. The coupling loss changes periodically with the period L_c. If we can obtain the propagation constant of the cladding mode, it is possible to minimize the coupling loss by setting the coupling length of the directional coupler at $l = \nu L_c$, where ν is an integer.

5. Conclusion

We proposed an analyzing technique based on a matrix method to calculate the effect of the coherent coupling in a directional coupler. It was experimentally confirmed that the cladding mode exists in actual semiconductor waveguides. It was found that a small periodic oscillation of loss of the transmitted light depending on the coupler length occurs due to the coherent coupling.

Acknowledgements

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