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Theoretical analysis method of vertical coupling optical I/O interface with mirrors

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Introduction

Compact optical input/output (I/O) interfaces which realize high optical coupling efficiency between optical waveguides and optical fibers are desired for utilizing photonic integrated circuits. Grating couplers that diffract lightwave for perpendicular direction to the incident optical beam are usually used as the optical interface. However, we must tilt optical fibers that couple to the grating couplers from vertical direction to the substrate in order to obtain high coupling efficiency because coupled optical power obtained from one side of the grating is limited to 50% when optical beam is perpendicularly incident to symmetric grating. This requires complicated structure in optical fiber connectors. We proposed an optical I/O interface which combines optical outputs from both side of the grating and realized high optical coupling efficiency [2]. However, the size of the I/O interface is large due to the coupling waveguides. In order to solve this problem, an optical mirror is located in one side of the grating in order to return optical output for the one side to the grating [3][4]. Numerical analysis as FDTD method is used for designing the structures.

In this study, we propose an analytical model with S parameters for designing the grating coupler with mirrors. This method enables us to design any structures that vertical coupling grating coupler with mirrors.

Grating coupler with Bragg-reflector

We analyzed for a structure of a grating coupler with an in-line Bragg-reflector as shown in Fig. 1 (a). The grating coupler diffracts incident light beam from vertical direction to the substrate toward the direction of optical waveguide formed on the surface. Bragg grating reflector is located in one side of the grating coupler in order to return optical output to the grating. The returned lightwave is diffracted again by the grating coupler and emitted toward perpendicular directions to the substrate. If the diffracted lightwave is anti-phase for the transmitted and reflected lightwave of the incident beam, maximum output power can be obtained for another side of the grating. Therefore, it is necessary to optimizing design of the structure in order to maximize optical coupling efficiency.

S-Matrix model of grating couplers

We analyzed the complicated optical I/O interface with a grating coupler using a scattering matrix. A grating coupler is a four port device which has four I/O ports for vertical and horizontal direction as shown in Fig. 1 (b). We defined a scattering matrix (S-matrix) model as shown in eq. (1).

$$\begin{bmatrix} O_1 \\ O_2 \\ O_3 \\ O_4 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{12} & S_{22} & S_{23} & S_{24} \\ S_{13} & S_{23} & S_{33} & S_{34} \\ S_{14} & S_{24} & S_{34} & S_{44} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} \quad (1)$$

Here, S_{ij} denotes an S-parameter for lightwave which incident from port j and diffracted for port i. Each S-parameters can be obtained by the FDTD calculation.

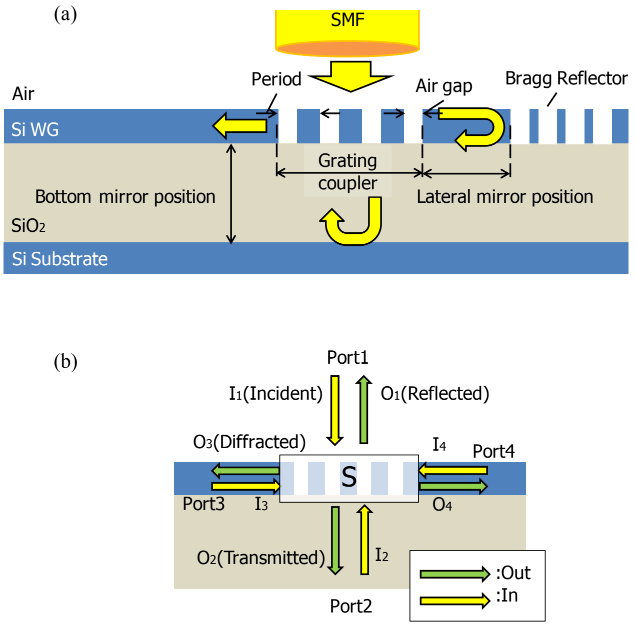

Fig.1 (a) Cross-section schematic of analyzed optical I/O interface
(b) Scattering matrix model of the grating coupler

S-Matrix model of the optical I/O interface

The optical I/O interface can be denoted as a two port device by blocking port 2 and port 4 off in Fig. 1 (b). Therefore, the S-matrix for the optical I/O interface can be described as eq. (2). Here, S'_{13} describes optical coupling efficiency between the input port (port 1) and output port (port 3). Therefore, to find the structure which maximize S'_{13} value is essential. The S'_{13} can be described by diffraction efficiency of the grating coupler itself "S_{13}" and the product of diffraction efficiencies of the grating coupler

$$\begin{bmatrix} O_1 \\ O_3 \end{bmatrix} = \begin{bmatrix} S'_{11} & S'_{13} \\ S'_{13} & S'_{33} \end{bmatrix} \begin{bmatrix} I_1 \\ I_3 \end{bmatrix} \quad (2)$$

"S_{12}" or "S_{14}" and reflectivity of the mirrors "R_b" or "R_l" as shown in eq. (3). Here, r_l denotes the product of lateral mirror reflectivity and phase rotation for round trip, r_b denotes the product of bottom mirror reflectivity and phase rotation for round trip as shown in eq. (4) and (5). According to these equations, higher coupling efficiency can be obtained for the structures of grating coupler with high diffraction efficiency and high reflective mirrors. Based on this knowledge, we optimized the structure of the grating coupler and the mirror.

$$S'_{13} = S_{13} + S_{23}R_bS_{12} + S_{34}R_lS_{14} + R_{lb} \quad (3)$$

$$R_b = \frac{r_b}{1 - r_bS_{22}} \quad (4)$$

$$R_l = \frac{r_l}{1 - r_lS_{33}} \quad (5)$$

$$R_{lb} = \frac{R_bR_l\left(S_{23}S_{24}\left(S_{14} + R_bS_{24}S_{12}\right) + S_{34}S_{24}\left(S_{12} + R_lS_{24}S_{14}\right)\right)}{1 - R_bR_lS_{24}{}^2} \quad (6)$$

Optimum structure of the optical I/O interface

Based on above mentioned method, we optimized optical I/O interface which is formed on an SOI wafer with 250 nm top Si layer (waveguide layer) for validating our analytical mode with S-matrix. The depth of the groove of the grating coupler and Bragg-reflector is 250 nm which is same as the thickness of waveguide core layer as shown in Fig. 1 (a) in order to simultaneously form silicon photonic wire waveguides core, grating coupler, and the Bragg-reflector with single dry etching process. The grating coupler was optimized for obtaining maximum diffraction efficiency"S_{13}" at 1.55μm wavelength by using FDTD calculation. The period of the grating, the line and space (L&S) ratio of the grating coupler, the periodic number of the grating was 588nm, 1:9, and 17, respectively. In this case the diffracting efficiency was 23.2%. The bottom mirror with reflectivity of 17.5% is formed by the interface of Si substrate and BOX layer. The Bragg-reflector was optimized for obtaining high reflectivity at 1.55μm by using FDTD calculation and multilayer film model. The period of Bragg-reflector is 320 nm and the L&S ratio is 7:3.

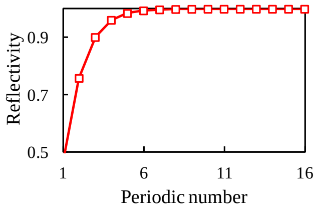

Fig.2 Reflectivity of Bragg-reflector

The periodic number dependence of reflectivity is shown in Fig. 2. Because the reflectivity reaches almost 100% when the periodic number is more than 8, the number of grating period is determined as 8. In this case, the reflectivity of the Bragg-reflector is 94.7%.

Finally, we optimized the positions of the lateral and the bottom mirrors in order to attain high coupling efficiency. Fig. 3 shows coupling efficiency as a function of two mirror positions calculated by the S-Matrix model and the FDTD calculation.

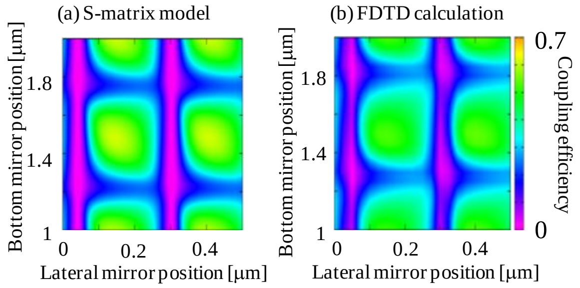

Fig.3. calculated coupling efficiency as a function of two mirror positions by using S-matrix model (a) and FDTD calculation (b), respectively

The result indicates that the analytical S-matrix model is in good agreement with the numerical FDTD calculation. The minor difference in the result is due to the error in S-parameters calculated by FDTD. We calculated each S-parameter based on the assumption that launched total optical power couples to fundamental mode of the waveguide, although in actual structure optical power which could not couple to the fundamental mode cannot be ignored. Therefore the effect of the unexpected higher-order modes causes the slight error in S-matrix model calculations. The maximum coupling efficiency is 54% when the lateral and the bottom mirror positions are 0.4μm and 1.5μm. It is more than double efficiency for the grating coupler without mirrors.

4. Conclusions

An analytical method using S-matrix model is proposed to design the I/O interface consisting of a grating coupler and mirrors. The validity of proposed scheme was proved by the comparison between S-matrix model and FDTD calculation. This method allows us to efficiently design any structures that vertical coupling grating coupler with mirrors.

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