RING-RESONATOR REFLECTOR WITH A WAVEGUIDE CROSSING

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ABSTRACT
We demonstrate the design and performance of a silicon-on-insulator ring-resonator reflector with a low-loss, low-crosstalk waveguide crossing. The device is simulated using the transfer-matrix method and a 2D finite-difference mode solver. It functions as a reflective-type notch filter and can be used for optical communications or thermal, biochemical, or other sensors. An extinction ratio of over 25 dB is observed experimentally.

INTRODUCTION
Waveguide ring-resonator selective reflectors are of great interest for many applications such as tunable lasers, reflective filters, and sensors [1], [2]. They have the advantages of easy fabrication, wide tuning ranges, and easy monolithic integration with other photonic devices. Whereas most of the designs of ring reflectors are reflective-type band-pass filters, H. Sun et al. [3] recently demonstrated a reflective-type notch filter as a promising biochemical sensor. Low loss, low crosstalk waveguide crossings enable more flexible routing and hence more complex photonic circuits. In this work, a new ring-resonator reflector is designed and demonstrated. Using a well designed waveguide crossing [4], it can achieve a high extinction ratio and, potentially, be used as a reflective notch filter in optical communications or as a thermal, biochemical, or other sensor.

DESIGN AND SIMULATION
Transfer-Matrix Analysis
As shown in Fig. 1, the reflection is achieved by “twisting” the ring-resonator using a waveguide crossing and two directional couplers. Assuming that the optical signal is input from the left port, i.e., incoming signal $E_{in} = a_1$ and $c_1 = 0$, we can calculate the reflected signal $E_r = d_1$ and through signal $E_t = b_1$ using the transfer-matrix method [2]. The function of a directional coupler can be described by a transfer matrix:

$$C = \frac{1}{i\kappa} \begin{bmatrix} -\tau & 1 & 0 & 0 \\ -T_c & \tau & 0 & 0 \\ 0 & 0 & -\tau & 1 \\ 0 & 0 & -T_c & \tau \end{bmatrix}$$

where $\kappa$ and $\tau$ are the coupling coefficients and $T_c = \kappa^2 + \tau^2$ is the total power transfer coefficient. The relation between the incident / reflective port and the transmissive port of the bus waveguide is given by:

$$\begin{pmatrix} a_1 \\ b_1 \\ c_1 \\ d_1 \end{pmatrix} = C_{12} P_{23} C_{34} \begin{pmatrix} a_4 \\ b_4 \\ c_4 \\ d_4 \end{pmatrix}$$

where $C_{12}$ and $C_{34}$ are the transfer matrices of the couplers. $P_{23}$ is the transfer matrix of the two optical paths, $L_1$ and $L_2$, and is given by:

$$P_{23} = \begin{bmatrix} P_{L1} & 0 & 0 & 0 \\ 0 & P_{L1}^{-1} & 0 & 0 \\ 0 & 0 & P_{L2} & 0 \\ 0 & 0 & 0 & P_{L2}^{-1} \end{bmatrix}$$

where

$$P_{L1} = t e^{-(i\beta+\alpha)L_1}$$

$$P_{L2} = t e^{-(i\beta+\alpha)L_2}$$

in which $\beta$ and $\alpha$ are the waveguide propagation constant and loss coefficient, respectively, and $t$ is the transmission coefficient of the waveguide crossing.

Fig. 1. Racetrack-ring reflector geometry with the transfer-matrix elements: $a (b, c, d)$ is the incident / output electrical field in the corresponding direction.
Parameters
We use the typical waveguide parameters for 500 nm wide, 220 nm high, silicon-on-insulator (SOI) nanowires in the modeling. The waveguide propagation loss is assumed to be $\alpha = 5 \text{ dB/cm}$. $t = 0.96$ is used for the transmission coefficient of the waveguide crossing [4]. The crosstalk of the waveguide crossing is better than $-40 \text{ dB}$ [4] and is ignored in the simulation. The power transfer coefficient of the couplers is assumed to be $T_c = 0.96$. A 2D finite-difference mode solver [5] is used for calculating the waveguide effective indices and the coupling coefficients of the directional couplers by following Ref. [6].

Optimal Coupling Coefficients
Critical to the design are the coupling coefficients of the directional couplers. Based on the dual-criteria of high reflectivity and high extinction ratio, it is found that the optimal coupling coefficients are $\kappa_{12} \simeq 0.84$ and $\kappa_{34} \simeq 0.77$.

MEASUREMENT AND PERFORMANCE
The device was fabricated at IMEC ePIXfab using a CMOS-compatible SOI technology [7]. The measurement schematic is shown in Fig. 2. Grating fiber couplers [7] are used for the input and output ports. A Y-branch power splitter, with an angle of 6 degrees between its two branches, is used to split the reflected light. The measured reflection spectrum, shown in Fig. 3, demonstrates that a Q factor of more than 10,000 and an extinction ratio of more than 25 dB can be obtained.

CONCLUSION
A novel ring-resonator reflector with a waveguide crossing has been designed and fabricated. It functions as a reflective-type notch filter. The high extinction ratio demonstrated experimentally shows that it has the potential to serve as a highly sensitive device for sensor applications and for optical communications.

ACKNOWLEDGMENT
The authors would like to thank CMC Microsystems and Lumerical Solutions Inc. for supporting this project and Dr. Nicolas Rouger at Grenoble University for fruitful discussions.

REFERENCES