A Design of Silicon-Based Racetrack Microcavity Resonator Using FDTD

S. Somkuarnpanit B. Puangkird and P. Koosirivanichakorn
Faculty of Engineering, KMITL, Chalong-Krung Rd., Ladkrabang, Bangkok, 10520, Thailand.
Phone:+66-2-326-9968, Fax: :+66-2-739-2398
Email: kssuripo@kmitl.ac.th

Abstract : This paper proposes a design of the racetrack microcavity resonator based on silicon substrate. The optimised dimensions of the structure were found by FDTD simulation. The characteristics were also found by the method, and further compared with another model of mode coupling theory. The optimised dimensions of straight guide at wavelength 1.55μm are thickness and width of 0.4 μm. The curve guide provides the maximum at 1μm whereas the resonating section require small coupling section of about 3μm.

1. Introduction

The racetrack microcavity resonator (RMR) has been developed from the structure of microring resonator (MRR), for used as wavelength filter, multiplexer, modulation and optical switch [1-5]. However MRR has poor energy transfer between the guides, consequently low efficiency. This can be overcome by insertion of a coupling straight section to the MRR, and resulting in the structure of RMR. RMR has dominant characteristics of wide free spectral range (*FSR*), finesse and *Q*-factor. Because of the benefit of mature fabrication process to provide the smallest structure [6], and the feasibility of electrical circuit integration, our interest then pays in the silicon substrate. Therefore, this paper would investigate the characterization of the racetrack microcavity resonator base on the silicon substrate using the most accurate method of the finite-difference time-domain (FDTD) [7-9] in the simulations.

2. Principles

There are basically three criteria in terms of the device dimension to characterize the resonator, e.g. the gap between the guides, the straight section and the curved section. For the first parameter, it is found that the coupling efficiency exponentially decays with the gap [1]. So, mostly will use the rule of thumb, that is gap used for the device should be as narrow as possible. The material technology seems to be the dominant factor for the gap, before the waveguides get fused together. The gallium-arsenide technology has the minimum gap at 300nm, whereas the silicon technology can get the gap down to 100nm [2],[3],[6]. Since the silicon technology has been well mature for structure of narrow gap – high coupling, and possibility to combine with another electronic circuits, so in the paper we will investigate the silicon-based racetrack resonator. The main issue here is to investigate the effect of the rest sections of the racetrack resonator, i.e. the straight and curved sections.

The Finite-Difference Time Domain (FDTD) algorithm has been used for the analysis in presence with perfectly matched layer absorbing boundary conditions [9]. Using the Maxwell's equation for the electric transverse mode, the E_y , H_x, H_z in lossless media can be formed. Consequently, the electric field along the guide can be found using the FDTD using these numerical Maxwell's Equations for TE mode.

$$E_y^{n+1}(i,k) = E_y^n(i,k) - \frac{1}{\varepsilon_0 n^2(i,k)}\frac{\Delta t}{\Delta x}\left[H_z^{n+1/2}(i+1/2,k) - H_z^{n+1/2}(i-1/2,k)\right] + \frac{1}{\varepsilon_0 n^2(i,k)}\frac{\Delta t}{\Delta z}\left[H_x^{n+1/2}(i,k+1/2) - H_x^{n+1/2}(i,k-1/2)\right] \quad (1)$$

$$H_x^{n+1/2}(i,k+1/2) = H_x^{n-1/2}(i,k+1/2) + \frac{1}{\mu_0}\frac{\Delta t}{\Delta z}\left[E_y^n(i,k+1) - E_y^n(i,k)\right] \quad (2)$$

$$H_z^{n+1/2}(i+1/2,k) = H_z^{n-1/2}(i+1/2,k) + \frac{1}{\mu_0}\frac{\Delta t}{\Delta x}\left[E_y^n(i+1,k) - E_y^n(i,k)\right] \quad (3)$$

3. The Structure and Analysis

The device structure used in the simulation is shown in Fig. 1. The parameters n_c, n_f and n_s are the refractive indices of air, silicon and silicon dioxide, respectively. The device was separately analysed into three sections: straight guide, curved guide and the resonating section. Firstly, the straight section was considered in its energy coupling efficiency between the straight guide and the racetrack, and the coupling length. It depends on the dimensions of the guide width, thickness and the spacing gap of the guides. The coupling efficiency decays exponentially with the latter, which is normally fixed with a narrow gap of 0.2μm from the current silicon technology. For the other parameter, the coupling length may be considered as a directional coupler.

Next, the curved section would affect the losses due to both bend loss and propagation loss. It is a trade-off between both losses. The bend loss would vary with R^{-n} whereas the propagation loss is proportional to R. Therefore, the compromise curvature must also be considered. The last section of racetrack structure could be analysed using the coupling mode theory [2], which employs Fig. 2 in the analysis. The travelling wave in the racetrack resonates at the wavelength λ_0 calculated by Eq. (4)

$$\lambda_0 = \frac{n_{eff}}{m}\left(2\pi R_{eff} + 2L\right) \quad ; \quad m = 1,2,3,\ldots \qquad (4)$$

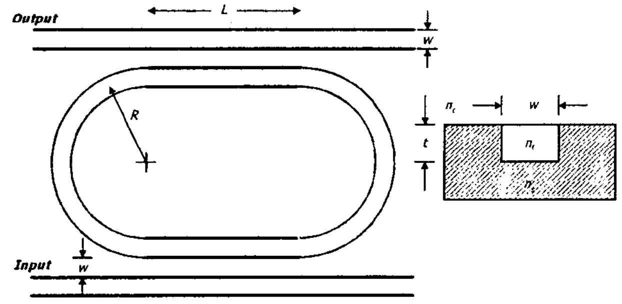


Fig. 1. The geometry of the racetrack resonator is used in the analysis

The transfer function of the device can be found using the coupling mode theory [2] by Eq.(5)

$$\frac{P_{out}}{P_{in}} = \frac{K^2 v_g^{\,2}}{\left(2\pi R_{eff} + 2L\right)^2 (\omega - \omega_0)^2 + v_g^{\,2}\left(K + \frac{P_{loss}}{2}\right)^2} \qquad (5)$$

where P_i and P_o are the energy of the waves at the input and the output of the RMR, respectively.

4. Transfer Characteristics

The performance characteristics are described as the *FSR*, bandwidth and the quality factor. The *FSR* could be found using (3):

$$\Delta\lambda_{FSR} = \frac{n_{eff}(m+1)(2\pi R_{eff}(m+1) + 2L)}{m+1} - \frac{n_{eff}(m)(2\pi R_{eff}(m) + 2L)}{m} \qquad (6)$$

And the half-power bandwidth with neglecting losses is determined by (4)

$$\Delta\lambda = \frac{2K\lambda_0^2}{2\pi(2\pi R + 2L)}\frac{v_g}{c} \approx \frac{K\lambda_0^2}{2\pi(\pi R + L)n_{eff}} \qquad (7)$$

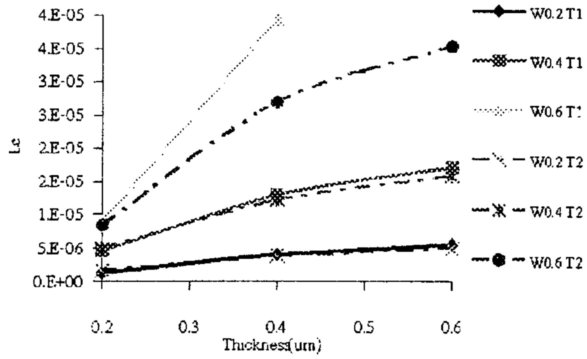
Having Used Eq. (7), the quality factor of the device can be determined by.

$$Q = \frac{\omega_0(\pi R + L)}{K v_g} \approx \frac{2\pi(\pi R + L)n_{eff}}{K\lambda_0} \qquad (8)$$

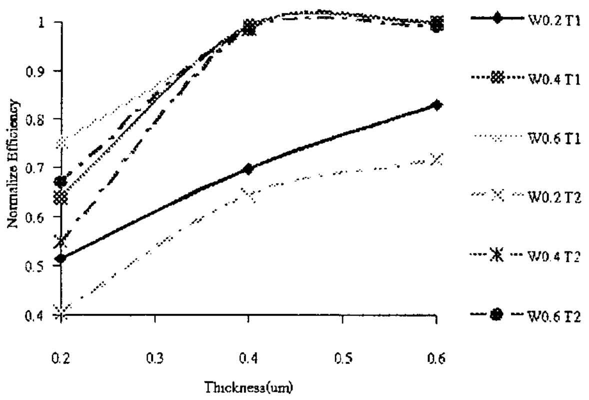
All equations above are determined by approximation group velocity to c/n_{eff}. The accuracy of the coupling mode theory is evaluated by comparing the obtained results of spectral response to those come out from the more rigorous FDTD simulation result in next section.

5. Numerical Results

In this section the silicon-based RMR was considered to propagate the TE mode wave at 1.55μm using FDTD method. The silicon core is embedded in the silicon dioxide, and opened surface to the air. From the FDTD simulation, the best dimensions of thickness and the width of the guide. Consequently, the coupling length corresponding with the dimension could be considered. Figure 2 shows the relationships between the coupling length and the efficiency of the straight section. It is found that the maximum efficiency occurs at the width from 0.4μm. For short coupling length, width from 0.4μm is chosen at the thickness of 0.4μm. This corresponds to the coupling length of 12μm.



(a)



(b)

Figure 2. The coupling length a) and the coupling efficiency b) the structure for the TE mode.

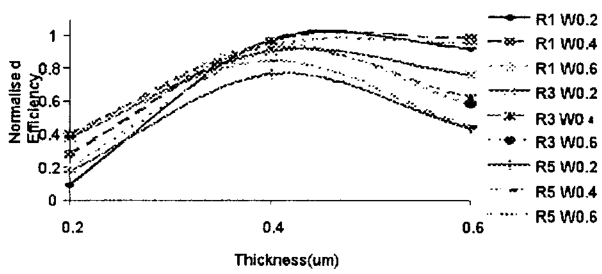


Figure 3. The normalised efficiency at various curved radius of the curved section.

Figure 3 shows the relationships of the normalised efficiency at various curved radius of the curved section. The power transfer is unlikely a proper function of curved radius. With the appropriate dimension mentioned, the adequate curved radius at 1μm provides feasibly small structure with relatively high efficiency.

For the last section forming resonance, the coupling length dominantly affect to spectral response as shown in Figure 4. The small fraction of coupling energy gives the high quality of spectral parameter: free spectral range, resonating quality, half-power bandwidth and finesse number. The appropriate coupling length would be around 0.3μm.

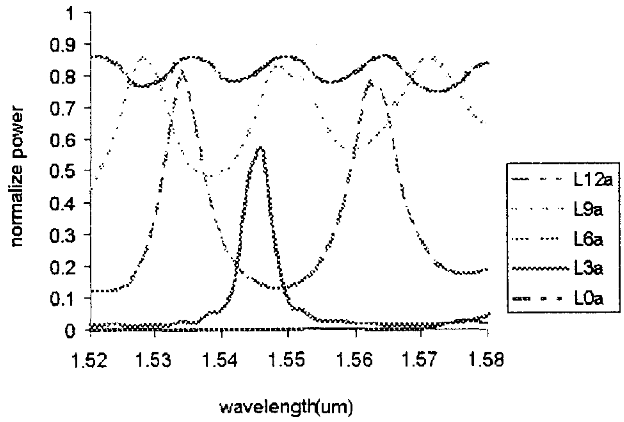


Figure 4. The normalised power transfer at coupling lengths of 0, 3, 6, 9 and 12μm...

6. Conclusions

This paper proposes a design of the racetrack microcavity resonator based on silicon substrate. The optimised dimensions of the structure were found by FDTD simulation. The characteristics were also found by the method, and further compared with another model of mode coupling theory. The optimised dimensions of straight guide at wavelength 1.55μm are thickness and width of 0.4 μm. The curve guide provides the maximum at 1μm whereas the resonating section requires small coupling section of about 3μm.

Refences

[1.] M. K. Chin, and S. T. Ho, "Design and modeling of Waveguide-Coupled Single-Mode microring Resonators," *J. Lightwave Technol.*, vol. 16, pp. 1433-1446, Aug 1998.

[2.] C. E. Little, et. al., "Microring Resonator Channel Dropping Filters," *J. Lightwave Technol.*, vol. 15, pp. 998-1005, June 1997.

[3.] B. E. Little, et. al., "Ultra-Compact Si-SiO$_2$ Microring Resonator Optical Channel Dropping Filters," *IEEE Photon. Technol. Lett.*, vol. 10, pp.549-551, April 1998.

[4.] K. Oda, N. Takato, and H. Toba, "A Wide-FSR Waveguide Double-Ring Resonator for Optical FDM Transmission Systems," *J. Lightwave Technol.*, vol. 9, pp. 728-736, June 1991.

[5.] S. C. Hagness, et. al., "FDTD Microcavity Simulations: Design and Experimental Realization of Waveguide-Coupled Single-Mode Ring and Whispering-Gallery-Mode Disk Resonators," *J. Lightwave Technol.*, vol. 15, pp. 2154-2165, Nov 1997.

[6.] R. A. Soref, "Silicon Based Optoelectronics," *Proc. IEEE*, vol. 18, pp. 1687-1706, Dec. 1993.

[7.] K. S. Yee, "Numerical solution of initial boundary value problems involving Maxwell'sequation in isotropic media," *IEEE J. Quantum Electron.*, vol.14, pp. 302-307, April 1966.

[8.] S. Chu, and S. K. Chaudhuri, "A Finite-Difference Time-Domain Method for the Design and Analysis of Guided-Wave Optical Structures," *J. Lightwave Technol.*, vol. 7, pp. 2033-2038, Dec 1989.

[9.] A. Taflove, *Computational Electrodynamics The Finite-Difference Time-Domain Method*, 1995 Artech House