Analysis of electro-optic switches with series-coupled multiple microring resonators*

YAN Xin(闫欣), MA Chun-sheng(马春生), ZHENG Chuan-tao(郑传涛), WANG Xian-yin(王现银), and ZHANG Da-ming(张大明)**

State Key Laboratory on Integrated Optoelectronics, College of Electronic Science and Engineering, Jilin University, Changchun 130012, China

(Received 5 December 2008)

In terms of the coupled mode theory, microring resonance and electro-optic modulation princeple, a reasonable project is proposed for designing an electro-optic switch with the series-coupled multiple microring resonators. The simulation and optimization are performed at the resonant wavelength of 1550 nm. The results are as follows: the core size of the microring is 1.6 μm×1.6 μm, the confined layer between the core and the electrode is 1.6 μm, the thickness of the electrode is 0.15 μm, the radius of the microring is 15.2 μm, the coupling gap between the microring and the channel is 0.14 μm, and the one between the microring and the microring is 0.6 μm, microring number *M* is 4, the switching voltage is 4 V, the insertion loss is 5.4 dB, and the crosstalk is –20 dB. The output spectrum is much flatter and much steeper than that of the single microring.

Document code: A **Article ID:** 1673-1905(2009)02-0081-4

DOI 10.1007/s11801-009-8167-y

A key issue in the evolution of optical communication networks is the availability of flexible photonic modules to manage a variety of operations, such as signal routing, wavelength demultiplexing and switching. The electro-optic switches with shorter switching time and faster switching speed are quite appealing for signal processing in optical system[1-4]. Continuous improvement of electro-optic switches plays a very crucial role in the transmission performance of optical communication systems. In particular, the reasonable selection of electro-optic materials is one of the efficient ways to improve the performance of electro-optic switches.

In the last decade, microring resonators (MRRs) have received considerable attention because of their some excellent features, such as low insertion loss, small crosstalk and easy integration of fabrication. In practical applications, the MRR filters should have the so-called box-like spectral response to reduce the need for accurate wavelength control[5]. In order to improve the Lorentzian spectral response and reduce the switching voltage of a single MRR, we can cascade multiple microrings serially to form an electro-optic series coupled MRR array.

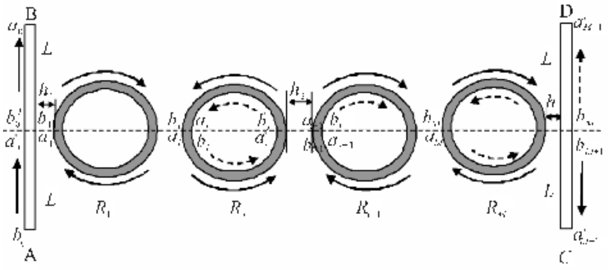
* This work has been supported by the National Natural Science Foundation of China (60706011), the National "973" Project of China(2006CB302803), the Fund of Chinese Ministry of Education (20070183087), and the Fund of Science and Technology of Jilin Province of China(20080125).

** E-mail: mcsheng@163.com

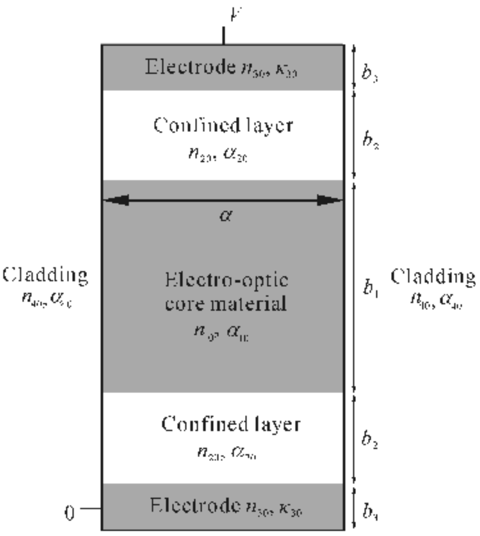
In this paper, by using the theories of the coupled mode, microring resonance and electro-optic modulation, a reasonable project is proposed for designing an electro-optic series-coupled MRR array switch.

Fig.1 shows the structural diagram and the cross-section of a polymer electro-optic switch with series-coupled multiple MRRs, which consists of *M* series-coupled microring and two channels (input/through channel and drop channel). The structure of the every microring is followed by: upper electrode/upper buffer layer/core/lower buffer layer/lower electrode/substrate, where only the waveguide core is electro-optic material. Denote R_1, R_2,… R_i,… R_M as the radius of the microrings, and assume that these microrings have an identical radius, $R_1 = R_2 = \ldots = R_M = R$. Let coupling gap between the microring and channel be h_1, and that between adjacent microrings be h_2. Let L be the distance from the input/through port to the coupling point.

When a voltage is applied on the electrode, the device becomes an electro-optic series-coupled multiple MRR switch, of which the principle is as follows. When the signal with the resonance wavelength is input from the port A, the applied voltage causes the variation of the refractive index of the electro-optic material of the microring core, and leads to the change of the mode propagation constant of the microrings, and then results in the phase shift in the microrings. As a result, the variation of the transmission powers in the microrings and the channels would occur. When the operation voltage is equal to the switching voltage, the power output from the drop channel will be the smallest, while the output from the through channel will be the largest, thus the switching function is realized in the device.



(a)



(b)

Fig.1 Structural diagram and cross-section of an electro-optic switch with series-coupled multiple MRRs.

First we give the relation between the operation voltage and the shift of the refractive index of the core electro-optic material. According to the electro-optic modulation theory, we can obtain the shift of the refractive index Δn_1 of the core electro-optic material versus the operation voltage V as

$$\Delta n_1 = \frac{1}{2} n_1^3 \gamma_{33} E_1 = \frac{n_1^3 \gamma_{33} V}{2\left(b_1 + 2b_2 n_1^2 / n_2^2\right)}, \tag{1}$$

where the operation voltage V can be equal to zero or not. The refractive index of the core electro-optic material n_1 will be changed to $n_1 + \Delta n_1$. Because other layers are non-electro-optic materials, n_2 ,n_3 and n_4 will be unchanged under the operation voltage.

Denote a_i'/b_i' and a_i/b_i to be the input/output amplitudes at the i-th coupling point respectively . For the M-th ring in Fig.1, $a'_{M+1}$and b_{M+1} are labeled at the under half of the drop channel when M is odd, or labeled at the upper half of the drop channel when M is even. According to the relations of the amplitudes between the microrings and channels, we give the transfer functions from the input port to the output of the input/through channel $\left|B\right|^2$ and that from the input port of the input/through channel to the output port of the drop channel $\left|D\right|^2$ as follows:

$$\left|B\right|^2 = \left|\frac{a_0}{b_0}\right|^2 = \left|\frac{P_{12}}{P_{22}}\right|^2, \ \left|D\right|^2 = \left|\frac{a'_{M+1}}{b_0}\right|^2 = \left|\frac{\exp(-j\psi)}{P_{22}}\right|^2, \tag{2}$$

with

$$\boldsymbol{P}_i = \frac{1}{j\kappa_i}\begin{pmatrix} \exp(-j\phi_i) & -t_i \exp(-j\phi_i) \\ t_i \exp(j\phi_i) & -\exp(j\phi_i) \end{pmatrix},$$

$$(i = 1,\ 2,\ 3,\ \cdots,\ M),\ \phi_i = \pi R(\beta - j\alpha_R),$$

$$\boldsymbol{P}_0 \boldsymbol{P}_1 \boldsymbol{P}_2 \cdots \boldsymbol{P}_M \equiv \begin{pmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{pmatrix},$$

$$\boldsymbol{P}_0 = \frac{1}{j\kappa_0}\begin{pmatrix} \exp(-j\psi) & -t_0 \exp(-j\psi) \\ t_0 \exp(j\psi) & -\exp(j\psi) \end{pmatrix},$$

$$\psi = L(\beta - j\alpha_L),$$

where α_L and α_{Ri} are the loss coefficients of the channels and rings, respectively, the corresponding intensity transfer functions (i.e. output powers) are defined as

$$P_{\mathrm{B}} = 10\log_{10}(|B|^2), \quad P_{\mathrm{D}} = 10\log_{10}(|D|^2). \tag{3}$$

In the following simulation, we select the resonance wavelength in free space λ_0= 1550 nm, the refractive index of the electro-optic polymer core n_1 = 1.613, its bulk loss coefficient α_1 = 0.25 dB/cm, and its electro-optic coefficient γ_{33} = 38.5 pm/V; the refractive index of the buffer layer n_2 = 1.461 [6], and its bulk loss coefficient α_2 = 0.25 dB/cm; the electrode is made of aurum, its refractive index n_3 = 0.19, and its bulk extinction coefficient κ_3 = 6.1[7]; the cladding beside the core is air, its refractive index n_4 = 1, and its bulk loss coefficient α_4 = 0. We take the distance from the input/through port to the coupling point to be L = 2000 μm , and the radius of all the microrings to be R = 15.2 μm , of which the bending loss coefficient is about 10^{-6} dB/cm, which is so small that it can be neglected. Therefore, the mode loss mainly arises from the absorption loss of the electrodes and the polymer materials. In the following analysis we have already taken account of the effect of the bending of the microring on the mode propagation constant using the analytical method of the bending waveguide presented by A. Melloni et al[8].

We optimize the values of some parameters of this kind of polymer device as shown in Fig.1, and investigate the transmission characteristics including the output spectrum, switching voltage, insertion loss and crosstalk. Calculation shows that when we select the core width and core thickness of the micoring within the range of 1.2-1.8 μm, in this case, the single mode propagation of the E_{00}^{y} mode is realized in the device, so we take $a = b_1 = 1.6$ μm.

Fig.2(a) shows the effect of the coupling gap between the microring and the channel h_1 on the output spectra P_D when the operation voltage $V = 0$, we take the number of the microrings M =4, coupling gap between two adjacent microrings $h_2 = 0.6$ μm, and that between the microring and the channel h_1= 0.04, 0.14, 0.24 μm, respectively, which is calculated from Eqs. (2) and (3). We find that as the coupling gap between the microring and the channel h_1 decreases, the non-resonant light becomes strong. If h_1 is too large or too small, for example $h_1 = 0.24$ μm or $h_1 = 0.04$ μm, the top of the spectral response is uneven, which will result in the harmful effect on the filtering of the device. Therefore, h_1 needs to be selected properly. For instance, when we choose h_1= 0.14 μm, in this case, the box-like spectral response is flat and precipitous.

Fig.2(b) shows the effect of the coupling gap between adjacent microrings h_2 on the output spectra P_D when the operation voltage $V = 0$, we take the number of the microrings M=4, coupling gap between the microring and the channel h_1= 0.14 μm, and the one between two microrings h_2= 0.5, 0.6 and 0.7 μm, respectively. We can also find that as the coupling gap between adjacent microring h_2 decreases, the non-resonant light becomes strong. If h_2 is too large or too small, for example $h_2 = 0.5$ μm or $h_2 = 0.7$ μm, the top of the spectral response is uneven, which will result in the harmful effect on the filtering of the device. Therefore, h_2 also needs to be selected properly. For instance, when we take h_2= 0.6 μm, in this case, the box-like spectral response is flat and precipitous.

Fig.2(c) shows the effect of the number of the microrings M on the output spectrum around the central wavelength. Where we take the coupling gap between the microring and the channel h_1= 0.14 μm, the one between adjacent microrings h_2=0.6 μm, and the number of the microrings M = 1, 2, 3, 4 respectively. We find that the larger the microring number M is, the more precipitous the spectral response and the weaker the nonresonant light become. However, when the number of the microrings M is too large, the spectral response becomes more uneven. Therefore, we had better choose M to be 4-6. Here, we select M = 4, then a flat and precipitous box-like filter response is formed.

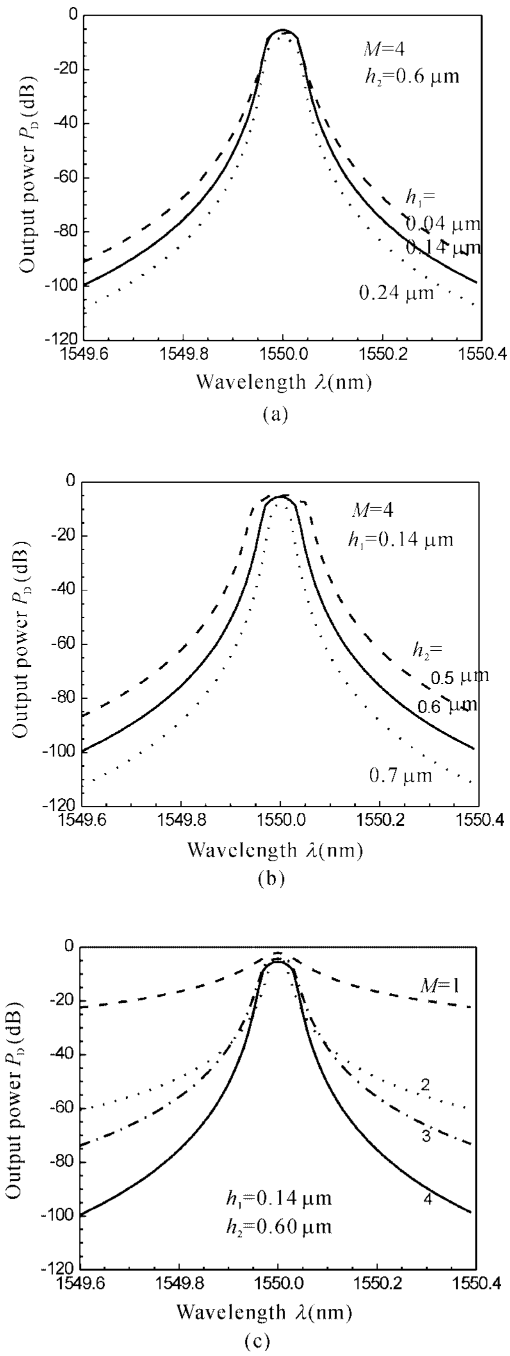


Fig.2 Effects of (a) coupling gap h_1 between microring and channel, (b) the h_2 between adjacent microrings, and (c) microring number M on output spectra P_D when $V = 0$, where $a = b_1 = 1.6$ μm, $b_2 = 1.6$ μm, $b_3 \to \infty$.

Fig.3 (a) and (b) show the curves of the output powers P_D (i.e. the peak values of the output spectra at wavelength of 1550 nm) versus the operation voltage V, which is calculated from Eqs. (1), (2) and (3).

Fig.3(c) shows the comparison of the curves of the output powers P_D versus the operation voltage V when we take

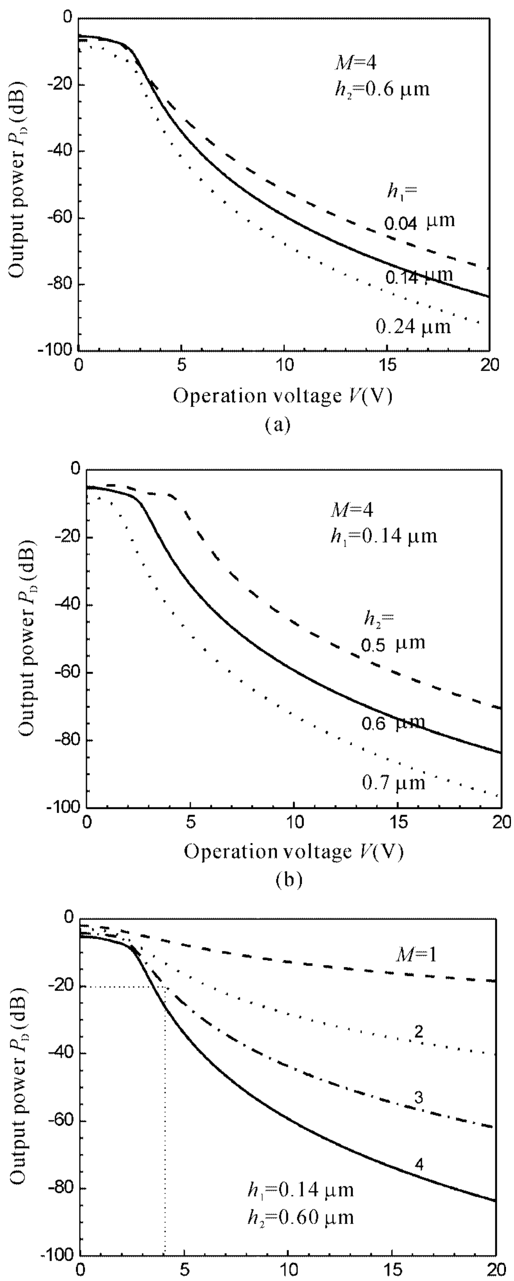


Fig.3 Effects of (a) coupling gap h_1 between microring and channel, (b) the h_2 between adjacent microrings, and (c) microring number M on output spectra P_D when $V\neq0$, where $a = b_1$ = 1.6 μm , b_2 = 1.6 μm, $b_3\to\infty$.

the M=1, 2, 3, 4, respectively. If we take the switching voltage as the operation voltage when the output power P_D drops to − 20 dB, we can find that the switching voltage of this series cascaded multiple microring structure is much smaller than that of the single microring structure. The larger the number of the microrings M is, the smaller the switching voltage becomes. The switching voltage is about 4 V for M = 4, while that of the device with a single microring is over 20 V. This indicates that the switching voltage can be reduced efficiently by using series-cascaded multiple microrings.

On the basis of the preceding analysis and discussion of the polymer electro-optic double series-coupled MRRs switches, conclusions are drawn as follows.

Under the operation wavelength of 1550 nm, we have carried out the optimum design of the device. By using the series-cascaded multiple microrings and by selecting proper parameters, the intensity of the non-resonant light can be reduced much weaker, the resonant peak of the output spectrum can be improved much flatter and much more precipitous, and the switching voltage can be decreased much smaller compared with the single microring structure. The designed device exhibits favorable switching functions, that is, the switching voltage is 4 V, the insertion loss is 5.4 dB, and the crosstalk is –20 dB

References

[1] J.H. Ji , X.L. Zhu, S.T. Dai and C.Y. Wang, Optics Communications , **270** (2007), 301.

[2] Z.P. Wang, D.W. Hu, X. Sun, Y. Wang, H.H. Yu, F.H. Xu, S. M. Dong, L. Wang and X.G. Xu, Optics and Laser Technology, **39** (2007), 72.

[3] E. Sarailou, A. Gharavi, S. Javadpour and V. Shkunov, Applied Physics Letters, **89** (2006), 171114.

[4] B.Zhao and S.J. Zhang, Applied Optics, **45** (2006), 2325.

[5] S.T Chu, B.E. Little, R.A. Wilson, and P.T. Ho, IEEE Photon. Technol. Lett., **11** (1999), 1426.

[6] C. Pitois, S. Vukmirovic, A. Hult, D.Wiesmann, M. Robertsson, Macromolecules, **32** (1999), 2903.

[7] W.G. Driscoll and W. Vaughanl, Handbook of Optics, McGraw-Hill, New York, pp. **7** (1978).

[8] A. Melloni, F. Carniel, R. Costa and M. Martinelli, Journal of Lightwave Technology, **19** (2001), 571.