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Analysis of a 1 × 32 polymer microring resonant wavelength de-multi/multiplexer assistant with interleave filter

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Abstract

A new 1 × 32 wavelength de-multi/multiplexer utilizing the microring resonator and interleave filter is proposed in this paper. A novel formula of transfer functions is presented, the parameters of microring are optimized, and the transmission characteristics of the system are analyzed. The channel spacing of the presented device is 0.4 nm. The analytical result shows that the crosstalk between adjacent channels can be reduced greatly and the filter response of the device can be improved by using the interleave filter. A bandwidth (3 dB) of 0.21 nm, an insertion loss less than 1.1 dB, and crosstalk below −32 dB were obtained for the optimized device. A method for compensating the manufacturing tolerances is discussed.

Keywords: Microring resonators; Interleave filter; DWDM; Transfer function

1. Introduction

Owing to the high-quality factors and compact size, microring resonators (MRRs) have been exploited for many optoelectronic applications such as filters [1–5], lasers, modulators [6], switchers [7,8], biosensors, etc. Among those applications, the most important and attractive applications of ring resonators are obviously channel dropping filters, due to their high wavelength selectivity and compact integration [9].

In wavelength-division-multiplexing (WDM) communication systems, especially dense wavelength-division-multiplexing (DWDM) systems, the most important and challenging requirement for filters is box-like response and fine wavelength controlling. It is the same for ring resonator filters. Many efforts of ring resonator filters were paid to the two aspects [4,10,11]. Behind those efforts is the tight fabrication control of microring structure. Apart from tight fabrication control arising from the above, in multi-wavelength applications, the tight fabrication control coming from the small radius increment of ring resonators of adjacent channels is also a problem. Theoretical calculation shows that the radius increment is in the order of 10 nm when channel spacing is 0.8 nm [12]. It is difficult for a conventional

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lithograph. So relaxation of this tight fabrication control should be considered.

As well known, an interleave filter can separate WDM signal channels having equal spacing into two groups: odd-number channels and even-number channels. Then, the channel spacing became double and has a response of comb filters. Additionally, the rectangular spectral response of the interleave filter can relax the specifications required for subsequent optical devices. The optical waveguide lattice interleave filter possesses designing flexibility and performance stability [13,14]. More importantly, this type of filter can be fabricated with planar light circuit (PLC) technology, which is important because integration with other integrated optical devices on one chip becomes possible and useful.

Based on the above considerations, a polymer microring resonator wavelength de-multi/multiplexers (MRRWDM), assisted with an interleave filter, was proposed and analyzed. The devices can de-multi/mulitiplex 32 deferent wavelengths around the central wavelength of 1.55 μm, with a wavelength spacing of 0.4 nm. Only de-multiplexing is analyzed in this paper.

This paper has four parts. First, in Section 2, a formula of transfer functions is presented for this MRRWDM assisted with an interleave filter. Second, in Section 3, some parameters of the device are discussed and optimized. Then, transmission characteristics, including box-like spectral response, de-multiplexing spectrum, insertion loss, and crosstalk are analyzed and the effect of the manufactured tolerance on the system performance is considered. Finally, some conclusions are summarized in Section 4.

2. Theory

In this section, the architecture and mechanism of the MRRWDM assisted with the interleave filter is described first. Then, parameters and transfer function of the interleave filter are obtained by using the half-band filter theory [15]. Finally, the transfer function of this device is presented by the transfer matrix theory.

2.1. Principle and configuration of the device

The configuration of the proposed device is depicted schematically in Fig. 1(a). It can be seen that this device includes two parts: one is the interleave filter and the other is the MRRWDM. The lattice waveguide-type form, which can be compatible with fabrication of PLC, was adopted to the interleave filter part [13,14]. This interleave is a maximally flat half-band filter, containing four Mach-Zelinder interferometers. The MRRWDM part consisting of 32 basic elements is divided into two rows. Each row consists of 16 basic elements connected in parallel. In each row, the increment of the ring radius between any two adjacent basic elements is $2\Delta R$. The increment of the ring radius between the basic filter elements in the bottom row and the corresponding basic element in the top row is ΔR. Fig. 1(b) shows the basic elements of the MRRWDM part. It is composed of two coupled rings with identical radii, which are vertically coupled to the input and output waveguide. The schematic cross-section of the overlap region between the ring and the bus waveguide is shown in Fig. 1(c). All the parameters used in this paper are shown in Fig. 1.

The main idea of the device is relaxing the filter response required for MRRWDM applied in DWDM systems, by introducing the interleave filter. When closely spaced signals are launched from the input port of the maximally flat half-band filter, it will be divided into two groups with the channel spacing becoming double. One group will be fed into the top row of the MRRWDM part, and the other group will be fed into the bottom row of the MRRWDM part. Then, different basic elements of MRRWDM will resonate at different wavelengths and will realize wavelength de-multiplexing.

2.2. Parameters and transfer function of interleave filter

The researcher of NTT proposed a newly modified lattice theory, which can simplify the lattice structure by a factor of two, and enable people to optimize the structure of low-loss flat-top interleave filters according to the desired performance [15]. Here, we adopt this theory to solve the parameters of the interleave filter, for example, θ_i, ϕ_i and ΔL, which are depicted in Fig. 1(a).

Then, using the transfer matrix technology, we can obtain the transfer matrix of the filter:

$$S_{\text{interleaver}} = S_N S_{N-1} \cdots S_0 = \prod_{N}^{0} S_k, \tag{1}$$

where

$$S_k = \begin{pmatrix} \cos\theta_k e^{-j(\varphi_k/2)} z^{-(1/2)} & -j\sin\theta_k e^{j(\varphi_k/2)} z^{-(1/2)} \\ -j\sin\theta_k e^{-j(\varphi_k/2)} z^{-(1/2)} & \cos\theta_k e^{j(\varphi_k/2)} z^{-(1/2)} \end{pmatrix}, \tag{2}$$

$$z = \exp(j(\beta - j\alpha)\Delta L. \tag{3}$$

Then relation (1) can be re-written as

$$S_{\text{interleaver}} = \begin{pmatrix} G(z) & jH_*(z) z^{-(2N-1)} \\ jH(z) & G_*(z) z^{-(2N-1)} \end{pmatrix}, \tag{4}$$

where the subscript * indicates a para-Hermitian conjugation defined as $G_*(z) = G^*(1/z^*)$.

The bar transfer function G and cross-transfer function H of the half-band interleave filter can be

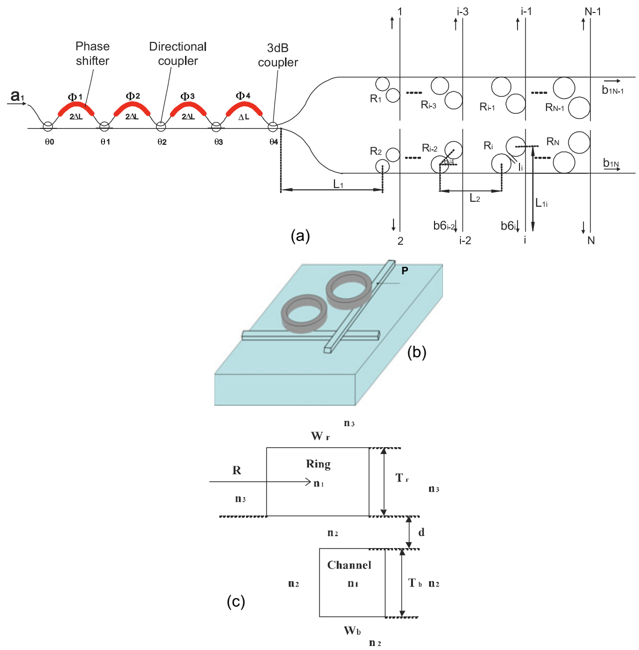

Fig. 1. (a) Diagram of an MRRWDM, combined with an interleave, (b) three-dimensional view of one MRRWDM basic element, (c) cross-sections at central point of coupling area between the ring and the channel.

obtained. Here, the coupled loss of the directional couplers is omitted and only the units' path length difference is taken into account.

2.3. Transfer function of vertical drop channel $|D_i|^2$

Let a'_{11} denote the input amplitudes of main channel and b'_{6i} denote the output amplitudes of the ith vertical drop channel. Then, the transfer function of the output port of the ith vertical channel, $|D_i|^2$, can be expressed as follows:

$$|D_i|^2 = \left|G\frac{b_{6i}}{a'_{11}}\right| = \left|G\left(\prod_{k=1}^{i-1} U_k\right) V_i \exp[-\mathrm{j}(i-1)\Psi_2]\exp(-\mathrm{j}(\Psi_{1i}+\Psi_1))\right|^2 \quad (5)$$

when i is odd

$$|D_i|^2 = \left|H\frac{b'_{6i}}{a'_{10}}\right| = \left|H\left(\prod_{k=1}^{i-1} U_k\right) V_i \exp[-\mathrm{j}(i-1)\Psi_2]\exp(-\mathrm{j}(\Psi_{1i}+\Psi_1))\right|^2 \quad (6)$$

when i is even, where

$$U_i = \frac{t_{1i}[1+\exp(-\mathrm{j}2\Phi_i)] - t_{2i}(1+t_{1i}^2)\exp(-\mathrm{j}\Phi_i)}{1-2t_{1i}t_{2i}\exp(-\mathrm{j}i\Phi_{1i}) + t_{1i}^2\exp(-\mathrm{j}2\Phi_i)}, \quad (7)$$

$$V_i = \frac{-\mathrm{j}k_{1i}^2 k_{2i}\exp(-\mathrm{j}\Phi_i)}{1-2t_{1i}t_{2i}\exp(-\mathrm{j}i\Phi_{1i}) + t_{1i}^2\exp(-\mathrm{j}2\Phi_i)}, \quad (8)$$

$$\Psi_1 = L_1(\beta - j\alpha_\mathrm{L}), \quad \Psi_2 = L_2(\beta - j\alpha_\mathrm{L}), \quad (9)$$

$$\Psi_{1i} = L_{1i}(\beta - j\alpha_\mathrm{L}), \quad \Phi_i = 2\pi R_i(\beta - j\alpha_{\mathrm{R}_i}), \quad (10)$$

where G and H are the bar and cross-transfer function of the half-band interleave filter, respectively, β is the mode propagation constant, and α_L and $\alpha_{\mathrm{R}_i}$are the mode loss coefficients of the channels and rings, respectively.

3. Results and discussions

In this section, the main parameters of the device are optimized, the transmission characteristics of the device are analyzed and the methods to improve the manufacturing tolerances are discussed.

3.1. Size of rings and channels

In order to reduce the polarization dependence and to assure single-mode operation in optical waveguides, the core size of the optical waveguides should be optimized. According to mode theory of optical waveguides [16], we found that when it is selected that $W_\mathrm{r} = 1.81$, $T_\mathrm{r} = 1.515\,\mu\mathrm{m}$ for the core width and thickness of the ring waveguides respectively, and $W_\mathrm{b} = 1.45$, $T_\mathrm{b} = 1.45\,\mu\mathrm{m}$ for the core width and thickness of the channel waveguides respectively, not only can the single-mode operation and the reducing of polarization dependence for both ring and channel waveguides be realized, but also the mode propagation constant β of the ring and channels can be matched. Fig. 2 shows the optimized results.

3.2. Radius and radius increment of rings

According to the microring resonant relations, the radius and radius increment of the ring, FSR, and the maximum number channels in one FSR can be obtained by using the following [12]:

$$R = \frac{m\lambda}{2\pi n_\mathrm{c}}; \quad \Delta R = \frac{1}{2\pi n_\mathrm{c}}\left(\lambda\Delta m + \frac{m n_\mathrm{g}}{n_\mathrm{c}}\Delta\lambda\right), \quad (11)$$

$$\mathrm{FSR} = \frac{\lambda n_\mathrm{c}}{m n_\mathrm{g}}; \quad N_\mathrm{max} = \mathrm{int}\left(\frac{\mathrm{FSR}}{\Delta\lambda}\right), \quad (12)$$

where $n_\mathrm{g} = n_\mathrm{c} - \mathrm{d}n_\mathrm{c}/\mathrm{d}\lambda$ is the group refractive index and $\Delta m = m_{i+1} - m_i$ is the resonant order increment between adjacent basic elements of MRRWDM. It means that different basic filter elements have different resonant orders. The reason for this selection will be described in the following.

It can be seen that when the material system, channel spacing, and maximum number of channels are given, the resonant order m and its increment Δm are the two main factors affecting radius and radius increment of the ring of MRRWDM. The relations among R, ΔR, FSR and N_max versus the resonant order m are shown in

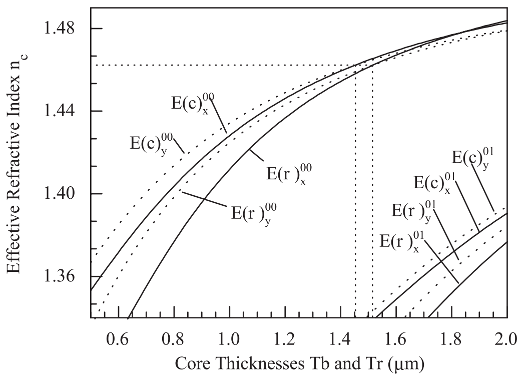

Fig. 2. Curves of effective refractive index nc versus core thicknesses T_b and T_r, where $W_b = 1.45\,\mu m$, $W_r = 1.81\,\mu m$, $E(r)_x$ and $E(r)_y$ correspond to the rings and $E(c)_x$ and $E(c)_y$ correspond to channels.

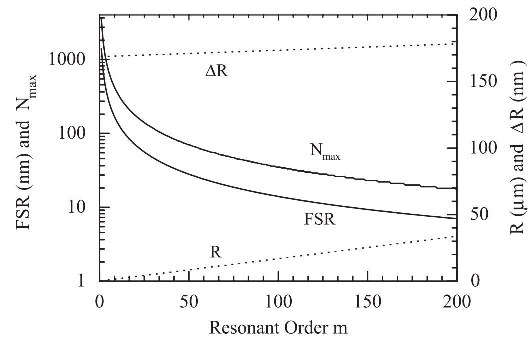

Fig. 3. Relations of R, ΔR, FSR, and N_{max} versus the resonant order of the central filter element, with Wr = 1.81, $T_r = 1.515\,\mu m$, and $\Delta m = 1$.

Fig. 3. The resonant order $m = 94$ can be determined with $R = 16.53\,\mu m$. See from fabrication of the device, both radius and radius increment of a ring need to be as large as possible. So $\Delta m = 1$ instead of $\Delta m = 0$ is selected to increase the radius increment from about 4 to 171 nm. It will be very helpful for reducing tight control of fabrication. Using the above parameters, the obtained radius of the largest basic element equals to 18.46 μm, corresponding to the smallest FSR of 12.84 nm. This FSR is sufficient for 32 channels with spacing 0.4 nm.

Calculations [17] also show that when the ring radius is larger than 15.5 μm, the bending loss coefficient of waveguides with high index contrast is much smaller than the typical value, $2\alpha_p = 0.5$ dB/cm, of the propagation loss coefficient at 1.55 μm. Therefore, only the propagation loss is taken into account in the following analysis. The optimized values of parameters for the polymer MRRWDM are listed in Table 1.

Table 1. Optimized values of device parameters

Central wavelength	$\Lambda = 1.550918\,\mu m$
Wavelength spacing	$\Delta\lambda = 0.4$ nm
Refractive index of polymer core of rings and channels	$n_1 = 1.56$
Refractive index of polymer cladding of channels	$n_2 = 1.34$
Refractive index of polymer cladding of rings	$n_3 = 1.0$
Relative refractive index difference	$\Delta n = 0.1410$
Core width of rings	$T_b = 1.81\,\mu m$
Core thickness of ring	$T_r = 1.515\,\mu m$
Core width and thickness of channels $W_b = W_r = 1.45\,\mu m$	
Resonant order of central ring	$M = 94$
Resonant order increment of adjacent filter element	$\Delta m = 1$
Radius of central ring	$R = 16.527\,\mu m$
Ring radius increment of adjacent filter element	$\Delta R = 173$ nm
Free spectral range	FSR = 14.876 nm
Number of vertical output channels	$N = 32$
Propagation loss coefficient	$2\alpha = 0.5$ dB/cm
Distance 1	$L_1 = 4000\,\mu m$
Distance 2	$L_2 = 250\,\mu m$

3.3. Parameters and response of the half-band interleave filter

The parameters of the interleave filter used in this paper are obtained by the half-band theory [15]. Here, a maximally flat filter with $N = 4$ is selected, with the response corresponding to the seventh order and channel spacing of 100 GHz. The transmittance of this filter is shown in Fig. 4. It can be seen that it has low loss, low crosstalk, and box-like spectral response.

3.4. Response and de-multiplexing spectra of the device

Fig. 5(a) shows the transmission spectrum of the central resonant peaks of MRRWDM. The filter response shape is normalized by 3 dB bandwidths of peaks in this figure. For comparison, the response of the MRRWDM basic element without half-band interleave filter is also given. It can be clearly seen that the MRRWDM assisted with an interleave filter shows much steeper roll off and superior out-of-band rejection. For example, the ratios of 15–3 dB bandwidths of MRRWDM without an interleave filter is 2.15, while that of the MRRWDM with an interleave filter is approximately 2.0. Fig. 5(b) shows the transmission spectra with different amplitude coupling ratios k_1 and k_2. Here, k_1 and k_2 are assumed to be matching, which means that the relation of $k_2^2 = \sqrt{0.25k_1^4}$ is adopted [4]. The bandwidth of 1, 3, 15 dB and the shape factor, defined by the ratios of 15–3 dB bandwidths, are listed in Table 2. The shape factor increases with the

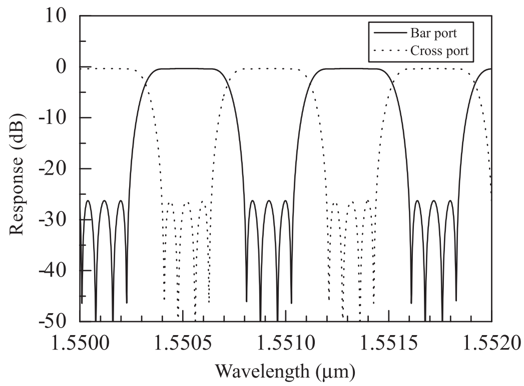

Fig. 4. Transmission spectra of 100 GHz channel spacing interleave filter, with device parameters listed in Table 1.

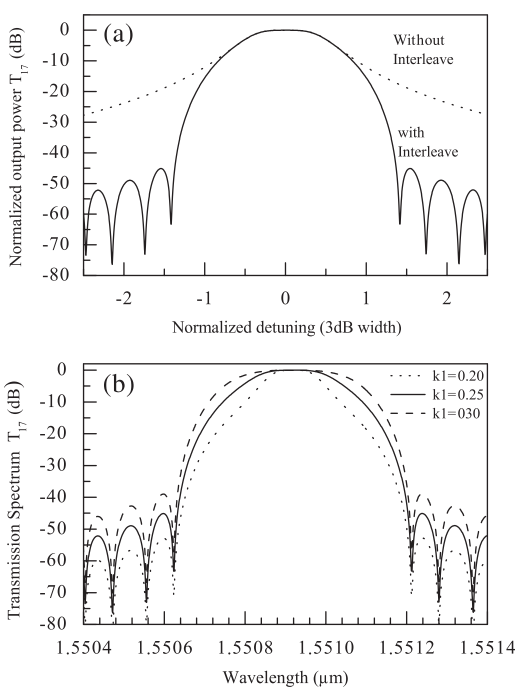

Fig. 5. Transmission spectra around central resonant wavelength of (a) without and with interleave filter, where $k_1 = 0.25$ and (b) the device with different amplitude coupling ratios. Note that the k_1 and k_2 are assumed to be matching.

amplitude-coupling ratio, while the power of resonance, which will result in the crosstalk at adjacent channels, is also increased. The ideal value for k_1 is about 0.25, among with k_2 equaling 0.0313.

Fig. 6 shows the demultiplexing spectrum of the presented device. It can be seen that 32 resonant wavelengths with a wavelength spacing of 0.4 nm are obtained at the corresponding vertical output waveguide, so 32 channels' wavelength de-multiplexing is realized in the presented device. It is found that the difference between the peak of the first channel and the 32nd channel is small.

Table 2. Normalized bandwidths of the device and ratios between them

k_1	−1 dB	−3 dB	−15 dB	15/3 dB
0.20	0.094 nm	0.1240 nm	0.312 nm	2.52
0.25	0.1440 nm	0.208 nm	0.410 nm	1.97
0.25*	0.147 nm	0.210 nm	0.450 nm	2.14
0.30	0.205 nm	0.292 nm	0.500 nm	1.59

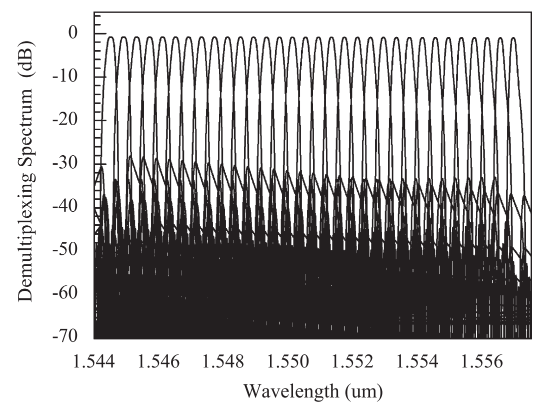

Fig. 6. De-multiplexing spectrum of the device with $k_1 = 0.25$, $k_2 = 0.0313$, and other parameters listed in Table 1.

3.5. Insertion loss and cross talk

The insertion loss and crosstalk of the *i*th vertical output channel are defined, respectively, as [17]

$$L^i(\lambda_i) = -10\log_{10}(|D_i(\lambda_i)|^2) \quad (i = 1, 2 \ldots N), \tag{13}$$

$$L^i_{\mathrm{CT}}(\lambda_i) = 10\log_{10}\left(\sum_{j\neq i, j=1}^{N} |D_j(\lambda_i)|^2 \Big/ |D_i(\lambda_i)|^2\right). \tag{14}$$

The insertion loss and crosstalk of all the output channels of the presented device are shown in Figs. 7(a) and (b), respectively. For comparison, those of the MRRWDM without a half-band interleave filter are also given. The insertion loss of the presented device is slightly larger than that of the device without an interleave filter. But the insertion loss of all output channels in the presented device is less than 1.1 dB. This indicates that a low loss can be realized in this structure, due to the low loss of the optical waveguide lattice filter based on PLC technology. The crosstalk of the presented device is much less than that of the device without an interleave filter. The main reason for this lies in the use of an interleave filter before MRRWDM. By using the interleave filter, the channel spacing for MRRWDM can be increased twice, which can greatly reduce the crosstalk between two adjacent channels. Additionally, the box-like response of the interleave

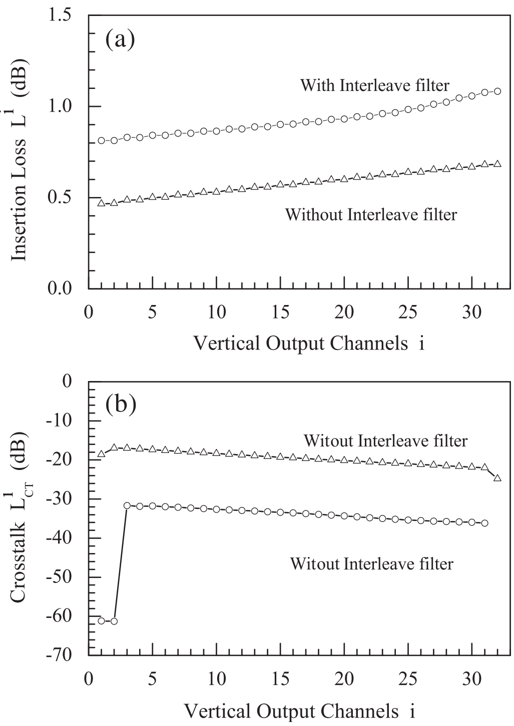

Fig. 7. (a) Insertion loss and (b) crosstalk of the device with $k_1 = 0.25$, $k_2 = 0.0313$, and other parameters listed in Table 1.

filter also contributes to decrease of crosstalk. The crosstalk of every channel of the device is below −32 dB, which is much lower than the device without the interleave filter by about 14 dB.

3.6. Discussion of manufacturing tolerances

In practice, the presence of manufacturing tolerances of device parameters, including δL, δR, δd, δa, δb and δn for path length L of MZIs of the interleave filter, the ring resonant radium R, coupling separation d, core width a, core thickness b, and core refractive index n, will severely affect the performance of the device [12,18]. The terms δL, δd, δa, δb, and δn will affect the response of the interleave filter, while the terms δR, δd, δa, δb and δn will affect the resonant wavelength of the microring. The path length errors δL can be compensated by using the heater, and the coupling errors resulting from δd can be reduced by new structural stabilized couplers [13]. The other terms δR, δa, δb and δn can be compensated by tuning the index of refraction of core or overlay, using either electro-optic effects or thermo-optic effects [5].

4. Conclusion

Based on planar light wave circuit (PLC) technology, we have proposed and designed a 32-channel multiplexer/de-multiplexer by using MRRWDM combined with a lattice interleave filter. The wavelength spacing of the device is 0.4 nm with the central wavelength at 1.55 μm. In order to increase the ring radius increment, the size of optical waveguide is designed to be low polarization dependent, and the rings of different MRRWDM basic elements are designed to be resonant at different resonant orders, which will greatly facilitate the fabrication of the device. Introducing the lattice interleave filter improves the response of the device and greatly reduces the crosstalk of the device. The proposed device has a box-like flat spectral response, of which the 3 dB bandwidth is about 0.21 nm. The insertion loss and the crosstalk for all channels are less than 1.1 dB and below −32 dB, respectively.

In summary, the designed device has excellent performance, with low polarization dependence, box-like flat spectral response, low insertion loss, and low crosstalk, which makes it interesting for DWDM optical communication systems.

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