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Design of Series-Coupled Microring Resonator Wavelength Filter Using Digital Filter Design Method

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Abstract
We propose a digital filter design method for a high-order series-coupled microring resonator (MRR). This method makes it easier to design MRR digital filters with the target parameters such as a 3 dB wavelength bandwidth, a free spectral range, and a centre wavelength. On the basis of this method, the filtering characteristics of the same and different circumference MRR filters are analysed.

1. Introduction

With the increase in the amount of information, wavelength division multiplexing (WDM) has been adopted in optical communication networks. The reconfigurable optical add/drop multiplexer (ROADM) is an important part of the next-generation WDM network [1]. It can effectively improve the flexibility and transmission speed of the optical network.

Wavelength filter is one of the technologies to realize ROADM. In recent years, the emergence of new process technologies has provided a technical basis for the realization of small-sized, highly integrated, making the filtering technology enter a new stage of high-speed development. Meanwhile, there are higher requirements for filtering characteristics. High-order series-coupled MRR filters have become popular among many researchers because of its compactness and high integration, and the large roll-off ratio of the response spectrum. So far, research and development of many MRR wavelength filters using silicon have been made [2]. However, a systematic design method for series-coupled high-order MRR with different parameters has not fully been established.

In this study, a design method of a series-coupled high-order MRR filter based on digital filter design is discussed. We have studied a design method for a compound semiconductor high-order MRR Chebyshev filter [3]. In this study, we discuss Chebyshev and Butterwort silicon MRR filters designed with the digital filter design method in more detail. Three target parameters can be considered simultaneously in the design process.

2. Digital filter design

The parameters to be designed as filter characteristics of MRR wavelength filter are the centre wavelength λ_0, the free spectral range (FSR), and the 3 dB wavelength bandwidth $\Delta\lambda$. In the field of digital filtering, the most commonly used digital filters are Butterworth filters and Chebyshev filters. Their gain function is given by

$$G_{N.\mathrm{Butt}}(\omega) = \frac{{g_0}^2}{1+\left(\frac{\omega}{\Delta\omega}\right)^{2N}}, \tag{1}$$

$$G_{N.\mathrm{Cheby}}(\omega) = \frac{{g_0}^2}{1+\left[\varepsilon C_N\left(\frac{\omega}{\Delta\omega}\right)\right]^2}, \tag{2}$$

where g_0 is maximum gain, ω is the angular frequency, $\Delta\omega$ is cut-off frequency, ε is the ripple factor, and C_N is a Chebyshev polynomial of the N-th order.

It can be known from equation (1) and (2) that the variable of the gain function is the angular frequency. In addition, the frequency response of the digital filter is not periodic. Therefore, it is necessary to convert the frequency domain to the wavelength domain and make it periodization.

In order to realize the conversion from the frequency domain to the wavelength domain, the frequency domain is converted to the complex domain (s) using $s = j\omega$. After that, it is converted into the z domain. The unit delay function $z = \exp(j\omega T_s)$ is used to achieve wavelength periodization. In addition, in an MRR filter, the unit delay can also be expressed as $z = \exp(j\beta L)$, β is propagation constant, L is microring circumference. Comparing the two types of unit delay function, the correspondence between the frequency and the wavelength domains are as follows:

$$\omega \to \frac{1}{\lambda}, \tag{3}$$

$$T_s \to \frac{2\pi\lambda_0^2}{FSR}, \tag{4}$$

$$\Delta\omega \to \frac{\Delta\lambda}{2\lambda_0^2}, \tag{5}$$

where T_s is a sampling period.

Taking a Chebyshev filter as an example, the pole expression method of the digital filter transfer function, and the transfer functions of Nth-order MRR filter are given by

$$H_{N.Cheby}(z) = \frac{\sigma_{N,Cheby}}{\prod_{k=1}^{N}(1-p_k z^{-1})}, \tag{6}$$

$$H_{N.MRR}(z) = \frac{\eta\gamma^N \prod_{n=0}^{N}\sqrt{K_n}}{|A_N(z)|}, \tag{7}$$

where p_k is the pole, and $\sigma_{N,\mathrm{Cheby}}$ is maximum gain, $A_N(z)$ is the function of unit delay, η is coupling loss, γ is loss coefficient, K_n is light power coupling efficiency, N is the number of MRR, z is the unit delay.

By comparing the coefficients of the simultaneous equations (6) and (7), the coupling efficiency can be obtained.

3. Design of fourth-order MRR using digital filter

Fig. 1 shows the calculation model of the MRR filter. We assume that the waveguides are made of silicon, and the propagation loss is set to 0.53 Np/cm (2.3 dB/cm). The transmittance in the coupling region is 0.998. The ripple factor of the Chebyshev filter is set to 0.3.

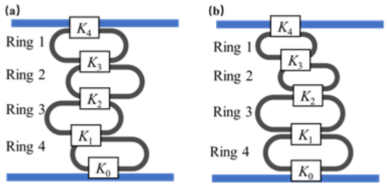

Fig. 1 Calculation models of fourth-order MRR filters. (a) Filter with same round-trip lengths, (b)Filter with different round-trip lengths.

3.1. Design of digital filter with same round-trip lengths

The target values of the parameters λ_0, FSR , and $\Delta\lambda$ are 1550 nm, 3.2 nm, and 0.6 nm, respectively. Fig. 2 shows the calculated spectral responses of the designed MRR filter with the same round-trip lengths.

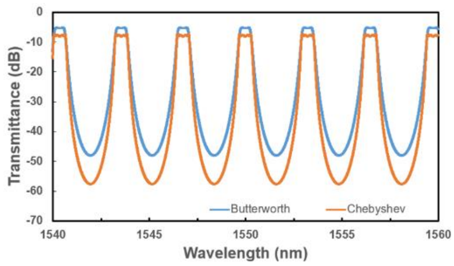

Fig. 2 Spectral responses of designed fourth-order MRR filters with same round-trip lengths.

Table I. Parameters obtained for digital MRR filter with same round-trip lengths.

	Chebyshev	Butterworth
Round-trip length L (μm)	214.4	
K_0, K_1, K_2, K_3, K_4	0.640, 0.125, 0.022, 0.306, 0.343	0.954, 0.503, 0.185, 0.136, 0.077

As can been from Fig. 2, the insertion loss of the Chebyshev MRR filter is approximately 7.2 dB larger than that of the Butterworth filter (5.0 dB). As with low pass digital filter, the spectral responses of the Chebyshev MRR filter have a better box-liked spectrum. Round-trip length and coupling efficiency can also be obtained, as shown in Table I.

3.2. Design of digital filter with different round-trip lengths

Some research work has shown that the Vernier effect can be used to extend the FSR of the filter [4]. Therefore, MRR filters with different round-trip lengths are designed in this part. The target parameters of λ_0, FSR, and $\Delta\lambda$ are 1550 nm, 35.2 nm, and 0.6 nm, respectively. Fig. 3 shows the calculated spectral responses of designed filters.

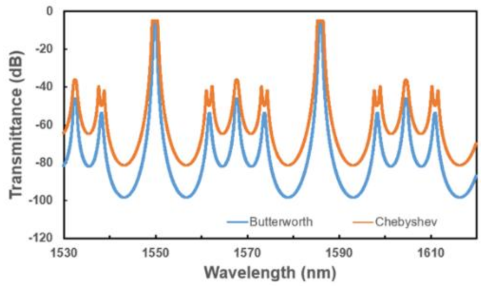

Fig. 3 Spectral responses of designed fourth-order MRR filters with different round-trip lengths.

The insertion loss of the Chebyshev MRR filter is approximately 4.7 dB smaller than that of the Butterworth filter (5.2 dB). It can be seen from Fig. 3 that the Butterworth filter has a more box-like spectrum in the Vernier structure, which is contrary to the results of the previous study in this structure [3]. In addition, the round-trip lengths and the coupling efficiencies of both filters are summarized in Table II.

Table II. Parameters based on digital MRR filter with different round-trip lengths.

	Chebyshev	Butterworth
Round-trip length L (μm)	39.3, 58.9	
K_0, K_1, K_2, K_3, K_4	0.199, 0.109, 0.008, 0.017, 0.312	0.134, 0.011, 0.0012, 0.024, 0.435

4. Conclusion

A design method for series high-order MRR filters based on the digital filter design method is proposed and discussed. The influence of the propagation loss coefficient on the characteristics of the digital MRR filter is analysed. It is possible to establish a systematic design method for filters based on higher-order MRRs, which makes it easier to design filters with target parameters.

Acknowledgments

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