

# Approaching to Genuine Monochromatic Light Filters Employing A Serially Coupled Triple Ring Resonator System

**Phichai Youplao**

Electrical Engineering Department, Faculty of Industry and Technology, Rajamangala University of Technology Isan Sakon Nakhon Campus, 199, Phungkon, Sakon Nakhon 47160, Thailand

E-mail: phichai3112@yahoo.com

**Abstract.** This paper presents the design and analysis of an optical channel drop filters configuration based on a serially coupled triple ring resonator system. The filtering characteristics of such the proposed ring configuration have been investigated by using the mathematical model simulation. In this work, the optical signal as a Gaussian pulse with a specified wavelength ranges from 1545 nm to 1555 nm is used to be the input signal that launches into and propagates through the ring resonators. Whereupon, the required optical channels are obtained at the drop port. The center wavelength of these filtering optical channels can be specified and controlled by selectively applying the suitable parameters to the system, such as each the ring radius and the coupling coefficients. From the simulation results, an ultra-narrow band optical channel with a spectral width at FWHM of approximately 12 pm can be achieved. Furthermore, an attempt to tune the filtering responses of the proposed system, by customizing the refractive index of the waveguide material, has been illustrated. By din of the tuning technique, the free spectral range shift between adjacent channels of approximately 46 pm, which corresponds to be less than 6.25 GHz of a channel spacing in DWDM system, can be actualized. The potential of using such the triple ring device for filtering application is performed and discussed.

## 1. Introduction

Present day, optical filters are one of the most important components in modern fiber-optic communication systems. Especially, for a wavelength division multiplexing (WDM) method, the optical filters are used to separate required optical channels from a combined optical signal without any required electronic systems. Various kinds of the optical filters have been investigated, such as arrayed waveguide gratings [1], Fabry–Perot filters [2], and photonic crystals [3]. In addition, although the photonic crystals are expected to be a promising platform for photonic integrated circuits due to its significant properties, such as the compactness, and spectral tunability. The filtering channel that can be obtained from the photonic crystal systems has remained as a large spectral width, e.g., about 10 nm [4].

Ring resonators have also been being received extensive attention as a useful component in optical communication systems. Many of its potential applications are demonstrated both theoretically and experimentally in many investigations, such as optical logic operators, optical switch, signal processing,



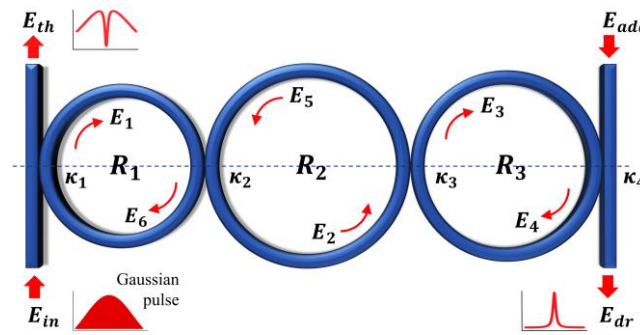
and filters [5-8]. However, it still needs to be further developed in order to improve the filtering responses.

In this paper, the primary aim is to achieve the analytical transfer functions of the serially coupled triple ring resonator system to be useful as an ultra-narrow band optical filter. Furthermore, the filtering characteristics that can be obtained by the proposed system and the attempt to tune its filtering response, by customizing the refractive index of the waveguide material, are demonstrated and discussed.

## 2. The Triple Ring Resonator System

The proposed ring resonator system of which the schematic diagram is shown in figure 1 is employed as an optical channel drop filter, which has an effective in filtering characteristics. In operation, the Gaussian pulse with a specified wavelength from the light source is used to be the optical input signal. This input light pulse is considered as a function that consists of a constant light field amplitude,  $E_0$ , and a random phase modulation, which is the combination of an attenuation term,  $\alpha$ , and a phase constant term,  $\phi_0$ , results temporal coherence degradation. The time-dependent input optical field,  $E_{in}$ , can be expressed as equation (1), where  $L$  is a propagation distance (waveguide length).

$$E_{in}(t) = E_0 \exp[-\alpha L + j\phi_0(t)] \quad (1)$$



**Figure 1.** A schematic diagram of the serially coupled triple ring resonator system

When a Gaussian pulse is propagating through the ring resonator system, in the direction as shown in the figure, the separate resonant outputs are formed. These output optical fields each at the throughput port and the drop port are represented by  $E_{th}$  and  $E_{dr}$ , respectively. The relations between each of the output,  $E_{th}$  or  $E_{dr}$ , and the input optical field,  $E_{in}$ , in each round trip calculation can be expressed as:

$$\left| \frac{E_{th}}{E_{in}} \right|^2 = \frac{(1-\kappa_1)(x_1-x_2+x_3)^2 - 2(x_1-x_2+x_3)(x_4-x_5+x_6)\sqrt{1-\kappa_1}e^{-\frac{\alpha}{2}L_1} \cos(knL_1) + (x_4-x_5+x_6)^2 e^{-\alpha L_1}}{(x_1-x_2+x_3)^2 - (x_1-x_2+x_3)(x_4-x_5+x_6)\sqrt{1-\kappa_1}e^{-\frac{\alpha}{2}L_1} \cos(knL_1) + (1-\kappa_1)(x_4-x_5+x_6)^2 e^{-\alpha L_1}} \quad (2)$$

$$\left| \frac{E_{dr}}{E_{in}} \right|^2 = \frac{\kappa_1 \kappa_2 \kappa_3 \kappa_4 e^{-\frac{\alpha}{2}(L_1+L_2+L_3)}}{(x_1-x_2+x_3)^2 - (x_1-x_2+x_3)(x_4-x_5+x_6)\sqrt{1-\kappa_1}e^{-\frac{\alpha}{2}L_1} \cos(knL_1) + (1-\kappa_1)(x_4-x_5+x_6)^2 e^{-\alpha L_1}} \quad (3)$$

Where the optical field that propagates within each the part  $i$  of the ring resonator system is  $E_i$  and the specified constant quantities of  $C_n$  and  $x_n$  are expressed as in Table 1.

**Table 1.** The expression of each the optical field  $E_i$  and the constant quantity of  $C_n$  and  $x_n$ 

The optical fields: $E_i$	The specified constant quantities: $C_n$ and $x_n$
$E_1 = E_{in}j\sqrt{\kappa_1} + E_6\sqrt{1-\kappa_1}e^{-\frac{\alpha L_1}{2}-jkn\frac{L_1}{2}}$	$C_1 = 1 - \sqrt{1-\kappa_2}\sqrt{1-\kappa_3}e^{-\frac{\alpha}{2}L_2-jknL_2}$
$E_2 = E_1j\sqrt{\kappa_2}e^{-\frac{\alpha L_1}{2}-jkn\frac{L_1}{2}} + E_5\sqrt{1-\kappa_2}e^{-\frac{\alpha L_2}{2}-jkn\frac{L_2}{2}}$	$C_2 = \sqrt{1-\kappa_3}\sqrt{1-\kappa_4}e^{-\frac{\alpha}{2}L_3-jknL_3}$
$E_3 = E_2j\sqrt{\kappa_3}e^{-\frac{\alpha L_2}{2}-jkn\frac{L_2}{2}} + E_4\sqrt{1-\kappa_3}e^{-\frac{\alpha L_3}{2}-jkn\frac{L_3}{2}}$	$C_3 = \sqrt{1-\kappa_2}\sqrt{1-\kappa_4}e^{-\frac{\alpha}{2}L_2-jknL_2}e^{-\frac{\alpha}{2}L_3-jknL_3}$
$E_4 = E_3\sqrt{1-\kappa_4}e^{-\frac{\alpha L_3}{2}-jkn\frac{L_3}{2}}$ (where $E_{add} = 0$ )	$C_4 = \sqrt{1-\kappa_2} - \sqrt{1-\kappa_3}e^{-\frac{\alpha}{2}L_2-jknL_2}$
$E_5 = E_4j\sqrt{\kappa_3}e^{-\frac{\alpha L_3}{2}-jkn\frac{L_3}{2}} + E_2\sqrt{1-\kappa_3}e^{-\frac{\alpha L_2}{2}-jkn\frac{L_2}{2}}$	$C_5 = \sqrt{1-\kappa_2}\sqrt{1-\kappa_3}\sqrt{1-\kappa_4}e^{-\frac{\alpha}{2}L_3-jknL_3}$
$E_6 = E_5j\sqrt{\kappa_2}e^{-\frac{\alpha L_2}{2}-jkn\frac{L_2}{2}} + E_1\sqrt{1-\kappa_2}e^{-\frac{\alpha L_1}{2}-jkn\frac{L_1}{2}}$	$C_6 = \sqrt{1-\kappa_4}e^{-\frac{\alpha}{2}L_2-jknL_2}e^{-\frac{\alpha}{2}L_3-jknL_3}$ and $x_n =  C_n $

Equation (2) and (3) indicate that the ring resonator system in this particular case is very similar to a Fabry–Perot cavity, which has an input and output mirror with a field reflectivity,  $(1 - \kappa)$ , and a fully reflecting mirror,  $\kappa$ , where  $\kappa$  is the coupling coefficient. The details of the specific variables are as follows: the linear absorption coefficient is  $\alpha$ , a roundtrip loss coefficient is  $e^{-\alpha L_i/2}$ , the linear phase shift is  $\phi_i = knL_i$ , where  $kn = 2\pi n/\lambda$ , and the refractive index of the ring waveguide is  $n$ . The waveguide length of the ring radius  $R_i$  is  $L_i = 2\pi R_i$ .

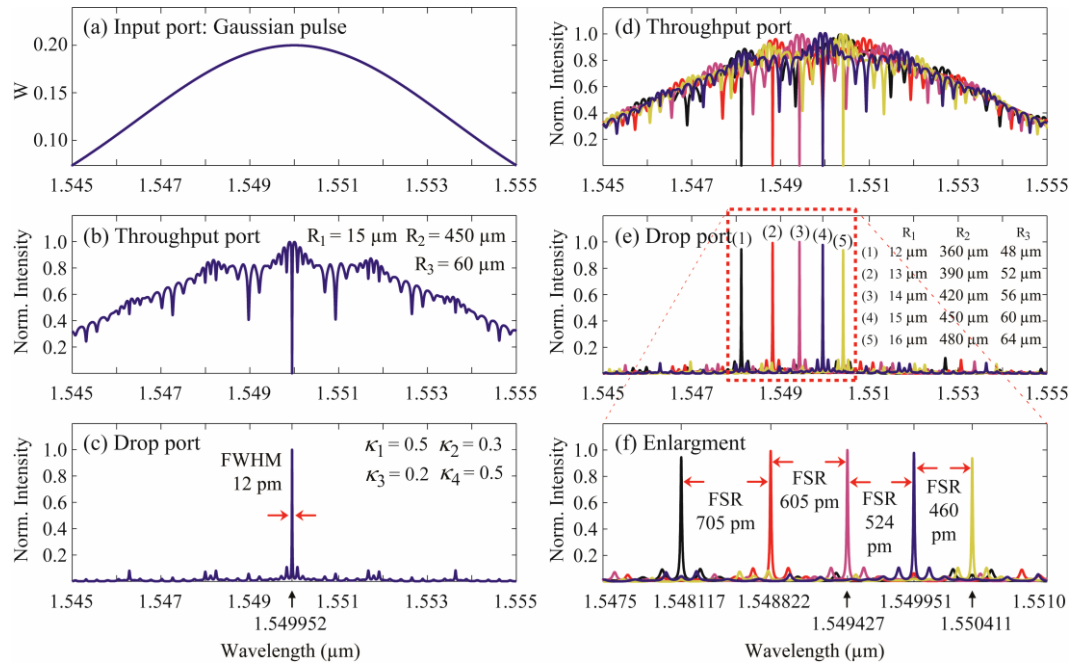
The input optical field,  $E_{in}$ , i.e. a Gaussian pulse from a laser source with the specified wavelength, is launched into the proposed ring resonator system with the appropriate parameters, such as the radius of the ring resonators, and the coupling coefficients, so that the transmitted output signals can be controlled.

From figure 1, in principle, the input light pulse is divided and sliced as the discrete signal propagates within the first ring,  $R_1$ , through the first coupling location of  $\kappa_1$ . Thereafter, it is spread to the other rings,  $R_2$  and  $R_3$ , through the coupling locations of  $\kappa_2$  and  $\kappa_3$ , respectively, in the direction as shown in the figure. Finally, after propagation in the proposed ring resonator, the required signals are obtained via the throughput port and the drop port of the system.

### 3. The Simulation Results

The optical Vernier effects that can be used for high-resolution distance measurement are commonly generated by using a resonant structure such as a micro-ring resonator [9]. For instance, a Gaussian input with a specified wavelength ranges from 1.545–1.555  $\mu\text{m}$  (C-band), 10 nm bandwidth, and a peak power of 0.2 W, as shown in figure 2(a), is launch and propagating through the proposed system. Thereafter, the resonant outputs each at the throughput port and the drop port are obtained with the optical Vernier effects. In addition, the Vernier effects are valuable and can be applied to advantage for filtering the optical ultra-narrow band under appropriate conditions.

In this work, the triple ring resonator system is proposed to be useful as an effective optical filter by din of the optical Vernier effects that resulting in its resonant outputs. In order to associate the system with a practical device [10, 11], the system parameters are specified as follows: the ring radii  $R_1 = 15 \mu\text{m}$ ,  $R_2 = 450 \mu\text{m}$  and  $R_3 = 60 \mu\text{m}$ . The refractive index of the waveguide material is fixed to be  $n = 3.47$  (Si–Crystalline silicon). The coupling coefficients,  $\kappa$ , of the system are ranged from 0.2 to 0.5. The waveguide loss is considered to be  $\alpha = 0.5 \text{ dB/mm}$ . For simplification, the optical field relation does not take into account the coupling losses [12].



**Figure 2.** The simulation results, (a) the Gaussian input, (b) and (c) the filtering characteristics that are obtained at the throughput port and drop port, respectively, (d) and (e) the filtering characteristics for changing the appropriate ring parameters as the five sets of the ring radius obtained at the throughput port and drop port, respectively, and (f) the enlargement of the figure (e).

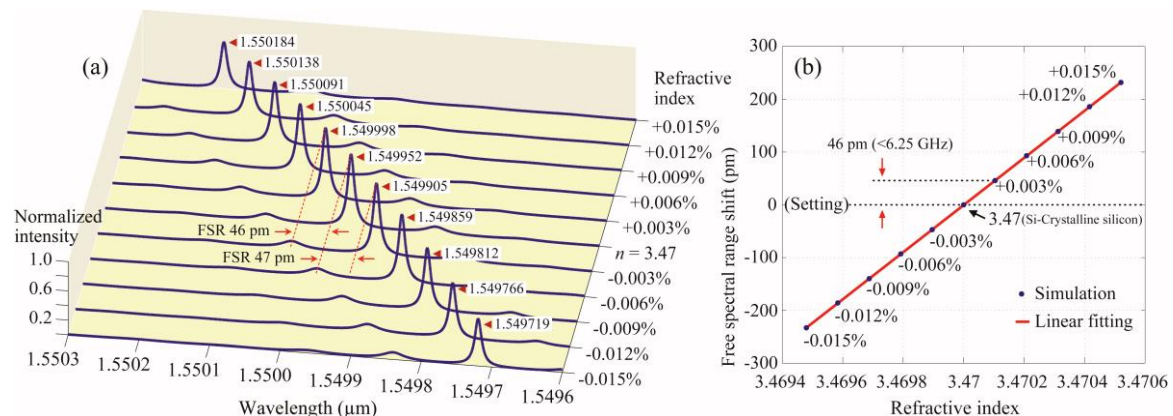
Figure 2(b) and 2(c) show the filtering characteristics that can be obtained via the throughput port and the drop port, respectively, where the filtering channel with a center wavelength of 1.549952  $\mu\text{m}$  and a spectral width of 12 pm, at FWHM, can be achieved.

The simulation results of the same input signal with the appropriate ring radius change for five sets as given in the figure are shown in figure 2(d) and 2(e). The output signals from the throughput port and the drop port of the system are superimposed in the figure, respectively. The enlargement of figure 2(e) is also demonstrated in figure 2(f). The filtering channels obtained from the drop port for each ring parameter set are at the center wavelengths of 1.548117  $\mu\text{m}$ , 1.548822  $\mu\text{m}$ , 1.549427  $\mu\text{m}$ , 1.549951  $\mu\text{m}$ , and 1.550411  $\mu\text{m}$ . The free spectral range shift between the adjacent channels is approximately of 705 pm, 605 pm, 524 pm and 460 pm, respectively.

#### 4. Discussion

In practice, the appropriated ring parameters that are selectively applied to the system, such as the ring radius, and the coupling coefficients, might have unavoidable errors in the fabrication process and result in the filtering characteristics of the actual device. However, the resonant characteristic of a micro-ring resonator can be tuned by dint of several methods. The most typical and straightforward approach for tuning the resonant response is to change the refractive index of the waveguide material, such as the thermo-optic effect method, which applies the heat to the material [13], and the electro-optic effect method, which applies the electrical field to the waveguide [14]. Therefore, the waveguide tuning techniques must be considered in the fabrication work for the actual device in order to function properly. Hence, in this study, an attempt to tuning the filtering characteristics of the proposed ring system is demonstrated. It can be performed by customizing the refractive index of the waveguide material, e.g., to be within  $\pm 0.015\%$  of the base refractive index value of the waveguide material (Si-Crystalline silicon;  $n = 3.47$ ). The simulation results for customizing the refractive index, with the same of the other ring parameters as shown in figure 2(b) and 2(c), are demonstrated in figure 3(a). By the well-known linear regression, the linearity relation of the free spectral range shift as a

function of the change in the refractive index is also illustrated in figure 3(b). As shown in the figure, the center wavelength of a filtering channel obtained from the drop port can be varied by customizing the refractive index of the waveguide material. Herein, the free spectral range shift between the adjacent channels of approximately 46 pm, which corresponds to be less than 6.25 GHz of a channel spacing in DWDM system (recommendation of ITU-T G.694.1) [15], can be actualized.



**Figure 3.** The results for customizing the refractive index of the waveguide material.

## 5. Conclusion

This article presents an optical waveguide configuration based on a serially coupled triple ring resonator system of which the design and analytical model are demonstrated to be useful as an optical channel drop filter. The resonant characteristics of the proposed system can be investigated by dint of its mathematical model simulation. These resonant responses can be controlled by selectively applying the suitable parameters to the ring system. From the simulation results, an ultra-narrow band optical channel with a spectral width of approximately 12 pm can be achieved. Moreover, by customizing the refractive index of the waveguide material, the filtering responses of the ring system can be tuned as approximately 46 pm of free spectral range shift between the adjacent channels. Therefore, due to such significant properties as the compactness, the spectral tunability, and especially in the filtering ability, the proposed ring system will be valuable for improving the performance of modern fiber-optic systems.

## References

- [1] W. Liu, G. Hu, H. Zhu, Y. Chen, Waveguide-metal–dielectric bi-layer gratings for reflective filtering and color security, *International Journal for Light and Electron Optics*. 126 (2015) 1245-1248.
- [2] Y. Li, B. Zhou, L. Zhang, S. He, Tunable Fabry–Perot filter in cobalt doped fiber formed by optically heated fiber Bragg gratings pair, *Optics Communications*. 344 (2015) 156-160.
- [3] H.A. Banaei, F. Mehdizadeh, M.H. Kashtiban, A new proposal for PCRR-based channel drop filter using elliptical rings, *Physica E*. 56 (2014) 211-215.
- [4] A. Taalbi, G. Bassou, M.Y. Mahmoud, New design of channel drop filters based on photonic crystal ring resonators, *International Journal for Light and Electron Optics*. 124 (2013) 824-827.
- [5] J.K. Rakshit, J.N. Roy, Micro-ring resonator based all-optical reconfigurable logic operations, *Optics Communications*. 321 (2014) 38-46.
- [6] X. Yan, C.S. Ma, C.T. Zheng, X.Y. Wang, D.M. Zhang, Analysis Of Polymer Electro-optic microring resonator switches, *Optics & Laser Technology*. 42 (2010) 526-530.
- [7] Y. Dumeige, C. Arnaud, P. Féron, Combining FDTD with coupled mode theories for bistability in micro-ring resonators, *Optics Communications*. 250 (2005) 376-383.

- [8] J.S. Li, Fast-tunable terahertz wave filter based on Kerr medium, *Optics & Laser Technology*. 56 (2014) 263-268.
- [9] R. Boeck, N.A.F. Jaeger, N. Rouger, L. Chrostowski, Series-coupled silicon racetrack resonators and the Vernier effect: theory and measurement, *Optics Express*. 18(24) (2010) 25151-25157.
- [10] H. Takara, T. Ohara, T. Yamamoto, H. Masuda, M. Abe, H. Takahashi, T. Morioka, Field demonstration of over 1000-channel DWDM transmission with supercontinuum multi-carrier source, *Electronics Letters*. 41(5) (2002) 270-271.
- [11] Q. Xu, V.R. Almeida, R.R Panepucci, M. Lipson, Experimental demonstration of guiding and confining light in nanometer-size low-refractive-index material, *Optics Letters*. 29(14) (2004) 1626-1628.
- [12] D.G. Rabus, M. Hamacher, U. Troppenz, H. Heidrich, Optical Filters Based on Ring Resonators With Integrated Semiconductor Optical Amplifiers in GaInAsP-InP, *IEEE Journal of Selected Topics in Quantum Electronics*. 8(6) (2002) 1405-1411.
- [13] M.B.J. Diemeer, Polymeric thermo-optic space switches for optical communications, *Optical Materials*. 9(1-4) (1998) 192-200.
- [14] I.L. Gheorma, R.M. Osgood, Fundamental limitations of optical resonator based high-speed EO modulators, *IEEE Photonics Technology Letters*. 14(6) (2002) 795-797.
- [15] Information on <https://www.itu.int/rec/T-REC-G.694.1-201202-I/en>