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Design Consideration Analysis of Optical Filters Based on Multiple Ring Resonator

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Abstract

Optical filters are the devices for channel adding or dropping in optical fiber based communication system. This paper described a simulation based design analysis on optical filters using multiple ring resonators. The ASPIC (a frequency-domain photonic circuit simulation tool) is used through the whole analysis. It is found that by using multiple rings and vernier effect it is possible to design narrow band optical filter. 10th order or even more ordered filter can be designed by using multiple ring resonators. If the number of rings is increased then the steepness of the filter response will also increase within certain limit.

Keywords: *Optical filter, Vernier effect, Multiple ring resonators.*

I. INTRODUCTION

OPTICAL filters which comprise ring resonators are actively researched nowadays. For telecom applications it is possible to use ring resonators for lasers, modulators, add-drop filters [1], [2] etc. Rings are also tested for biological, chemical and physical sensor devices. Indeed, their resonance frequencies are very sensitive to the micro scale environment of the ring, so a small stimulus provides a noticeable resonance frequency change. For ultra compact higher order optical filters, ring resonators are the best choice [3]-[7]. Most of the cases these type of filters are used for optical signal processing [8]. A standard type of ring resonator (Fig. 1) consists of a circular waveguide region with 2 straight waveguides. Due to close proximity of the straight bus waveguides to the ring, evanescent wave coupling occurs between the respective waveguide modes [9]. Optical feedback in the ring will cause the travelling wave to interfere with itself, resulting in the transmission spectra (Fig. 2). In case of a lossless cavity, all power can be extracted from the input waveguide at resonance and transferred to the drop port. Therefore, such a configuration acts as a channel drop filter. By exciting the add port with a signal at the resonance wavelength, the dropped signal can be replaced and one obtains an add-drop filter. Such filters can be used e.g. in the nodes of a Wavelength Division Multiplexing (WDM) ring network, where each node in the network has to be able to add and drop a limited number of wavelength channels [10]. The main advantages of this type filter in WDM application are less distortion and minimum interference. This type of filters comprises two or more ring either in parallel [11], [12] or in series [13], [14] configuration. This type of optical filter design depends on different parameters. One of the most important parameters is the coupling parameter [15]-[19]. These types of related parameters of ring resonator based filters are analyzed here through simulation. The common ways or factors those we need to consider before the final fabrication of optical filters are analyzed and discussed here. This is important because the fabrication process of optical filters is costly and so sensitive.

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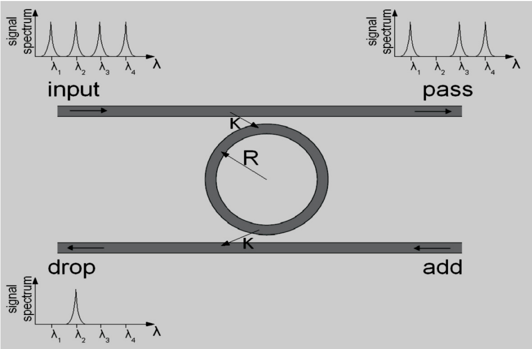

Fig. 1. Operation principle of a ring resonator based add-drop filter.

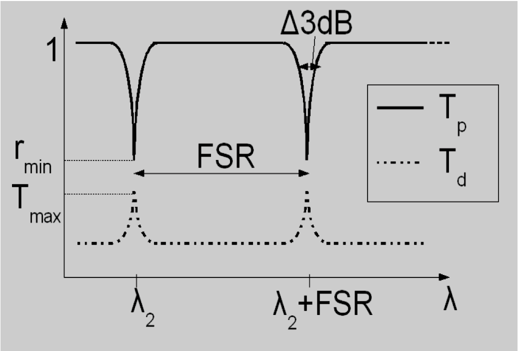

Fig. 2. Illustration of the add and drop spectrum of a ring resonator.

II. MATHEMATICAL THEORY

In order to have an idea of the influence of different parameters on the operation of the resonator, it is interesting to have a look at the following equations. Let κ be the amplitude coupling between ring and bus waveguides, and $\tau = \sqrt{1-\kappa^2}$ in case of a lossless coupler. Let A be the amplitude transmission of half a roundtrip around the ring, excluding coupling to the bus waveguides. The definition of the ring radius can be chosen rather arbitrarily, but the effective index $n_{eff} = n_{eff}^R + j.n_{eff}^I$ is always related to the radius definition chosen. With α the amplitude extinction coefficient of the travelling wave in the ring (in 1/cm), and L half the ring roundtrip length,

$$A = e^{-\alpha L} = e^{-\frac{2\pi}{\lambda} n_{eff}^I L} \tag{1}$$

Let $\phi = 2\beta L$ be the phase accumulated over a roundtrip (with β the propagation factor of the ring waveguide mode). For a symmetrical coupled resonator, the drop port power transmission can be calculated:

$$T_d = \frac{T_{\max}}{1 + F \sin^2\left(\frac{\phi}{2}\right)} \tag{2}$$

$$T_{\max} = \frac{\kappa^4 A^2}{\left(1 - \tau^2 A^2\right)^2} \tag{3}$$

$$F = \frac{4\tau^2 A^2}{\left(1 - \tau^2 A^2\right)^2} \tag{4}$$

The pass (through) port power transmission is-

$$T_p = \frac{r_{\min} + F \sin^2\left(\frac{\phi}{2}\right)}{1 + F \sin^2\left(\frac{\phi}{2}\right)} \tag{5}$$

$$r_{\min} = \frac{\left(1 - A^2\right)^2 \tau^2}{\left(1 - \tau^2 A^2\right)^2} \tag{6}$$

Within a linear approximation of the dispersion curve of n_g (constant group index), the free spectral range is given by-

$$\Delta\lambda_{FSR} = \frac{\lambda^2}{n_g 2L} \tag{7}$$

Still with L the half ring roundtrip. The 3dB-bandwidth is given by-

$$\Delta\lambda_{3dB} = \frac{\left(1 - \tau^2 A^2\right)\lambda^2}{\tau A \pi 2 L n_g} \tag{8}$$

And the quality factor Q of the resonator (with bus waveguides) is-

$$Q = \frac{\tau A \pi 2 L n_g}{\left(1 - \tau^2 A^2\right)\lambda} \tag{9}$$

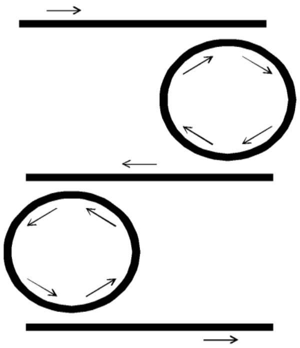

Fig. 3. Structure that may exhibit the Vernier effect.

III. MULTIPLE RINGS

Multiple ring resonators are widely used in case of optical filtering. Here we used three different configurations to investigate the design consideration about the optical filter [20].

Two ring waveguides could be configured with two bus waveguides to construct a Vernier effect structure where the second ring will only resonate with the resonance wavelengths from ring one and hence, function as a filter when it's Free Spectral Range (FSR) is larger than the FSR of the first ring. Here we will not worry about different polarizations. Therefore, we only change TE parameters and perform TE calculations. In addition, to keep the tasks general, we do not implement specific material systems. However, these have a big influence on actual designs. e.g. high-contrast systems can implement tighter bends, so smaller rings with larger free spectral ranges are possible. For simplicity we will work with the optical length (optical length = index * geometric length). In addition, no dispersion will be included so the effective index equals the group index.

A. Vernier Effect

Without decreasing the ring circumference there is a way to suppress interstitial microring resonances to generate an extended, virtual FSR which is known as Vernier Effect [21], [22]. As mentioned in [23]-[26] we can write Free Spectral Range (FSR)-

$$FSR = \frac{c}{n_{eff}\left(L_2 - L_1\right)} \tag{10}$$

L_2 & L_1 are the circumference of the two rings, c is the velocity of light and n_{eff} is the effective refractive index.

With the help of Vernier effect we can increase the free spectral range. This effect can arise with two coupled add-drop filters: the drop of the first one is coupled to the input of the second one (Fig. 3).

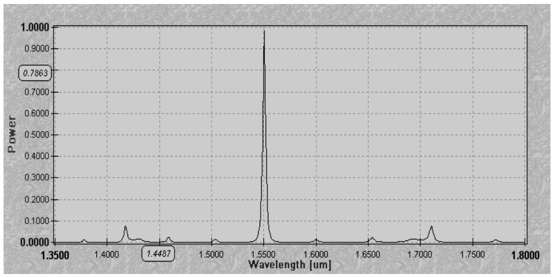

Fig. 4. Output of the filter while using vernier effect.

By using this vernier effect we can make a sharp filter at a specific wavelength. For this simulation we have chosen the wavelength as 1.55 μm and it is calculated that if the FSR is 0.132 μm then the ring resonator can be used as a filter for 1.55 μm wavelength with optical length as-

$$\frac{\lambda^2}{2Ln_g} = 0.132\ \mu m$$
$$\Rightarrow 2Ln_g = 18.198\ \mu m$$

So we can design a sharp filter for a specific wavelength using this vernier effect. The output of such filter is shown in Fig. 4. Here we designed the filter for the telecom wavelength. And it is clearly observed that the filter response is sharp or this filter will only filter out the 1.55 μm wavelength and will be inactive for other wavelengths.

B. Two Rings Coupled in Parallel

In WDM networks it is often necessary to have flat filters with a steep Roll-off. This is achievable through combinations of rings, so one obtains higher order filters. Now let us consider a new structure as shown in Fig. 5, two bus wave guide and two rings in parallel configuration. So now the coupling will be between bus waveguide and first ring (κ_1), first ring and second ring (κ_2), second ring and bus waveguide (κ_3). In the Vernier structure, the two rings are coupled through another waveguide but in parallel ring structure the two rings are directly coupled to each other.

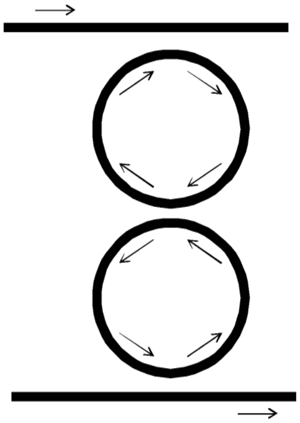

Fig. 5. Rings coupled in parallel.

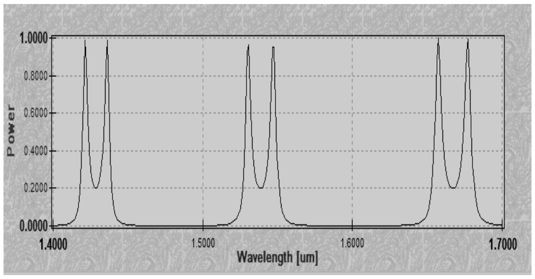

Fig. 6. Output for two coupled parallel ring having same coupler strength $(\kappa_1^2 = \kappa_2^2 = \kappa_3^2 = 0.2)$.

In this case the design consideration depends on the coupling strength (κ). If all three couplers have the same strength then we have the output as shown in Fig. 6. So it is observed that for the same coupling strength we are having two peaks at each filtering section. So another design consideration is that we have to choose the coupling strength very carefully and in an optimized way. It is possible to obtain flat, steep filter response for the resonance around 1.55 μm if we choose the values of κ^2 as follows –

$\kappa_1^2 = 0.7, \kappa_2^2 = 0.1, \kappa_3^2 = 0.1$ or
$\kappa_1^2 = 0.1, \kappa_2^2 = 0.1, \kappa_3^2 = 0.7$

So the corresponding output that was found is shown in Fig. 7. Here we kept the lengths of the rings identical, changed the coupler strengths with respect to each other and also kept two of the three couplers equal.

C. Two Rings Coupled in Series

Considering a series configuration of ring resonators, we can have a new filter type. There is a well explanation in [27] about rings in series. In this case we consider identical rings in series and varying the length in between (Fig. 8). For this kind of structure we got the output as shown in Fig. 9.

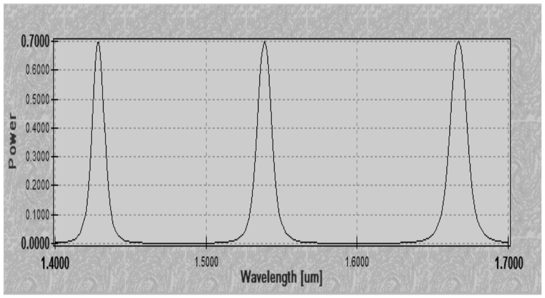

Fig. 7. Output for two coupled parallel ring having flat, steep filter response.

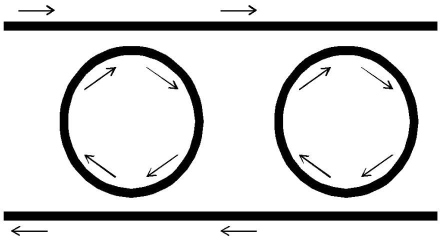

Fig. 8. Rings coupled in series.

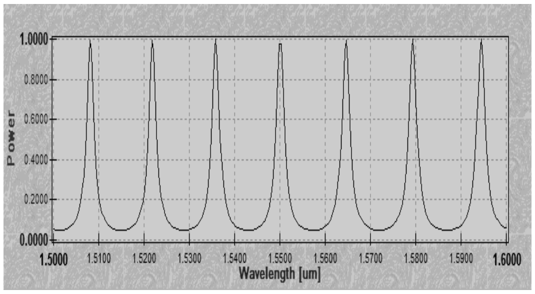

Fig. 9. Output for identical rings in series.

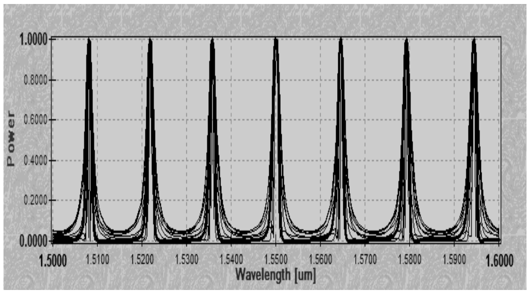

Fig. 10. Output for identical rings coupled in series after varying the length in between.

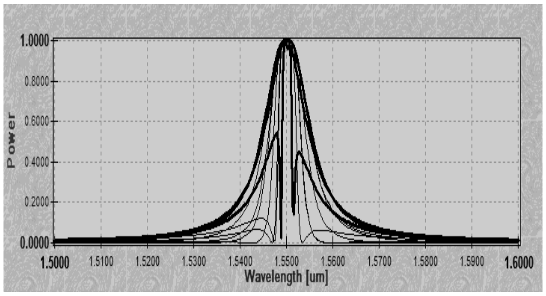

Fig. 11. Symmetric, centralized output at 1.55 um for identical rings coupled in series.

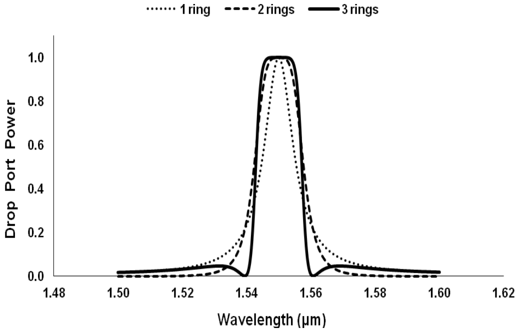

Fig. 12. Output with three rings in series.

For simplicity, the ring bus lengths are set to zero. We varied the waveguide length in between. While varying the waveguide lengths we got some kinds of periodicity in the output as shown in Fig. 10.

If the rings are made to be 10th order filters with 15.5 μm length then a periodicity of 1 The is observed for a waveguide length of 0 to 3.89 μm where the peak repeats itself. A mirror is seen in between length 1.67 μm and 2.22 μm. The in between length used from 0 to 3.889 μm, and we got the output with periodicity as shown in Fig. 11. So we obtain a two-ring filter with the following properties: symmetric, centralized at 1:55 μm, steeper edges than a single ring filter.

For three rings in series, a filter is obtained for a waveguide length = 1.55/4 = 0.3875 μm. We see in Fig. 12 that the steepness increases as the number of rings increases from the 1st ring to the 3rd ring.

So to design a filter with steep response based on ring resonator it is important to choose more than two rings but there is also some limitation to use lot of rings.

IV. CONCLUSION

From the above analysis we can say multiple rings can be arranged in series and parallel. Parallel rings could be fabricated as flat filters with steep roll-off. In a series structure, the variation of the length in between them gives a periodic change of filter roll-off. The narrowest distance would be when we have only 1 period between them. It is observed that if the number of rings is increased in series, the steepness for symmetric filters increases. So ring resonator works on the principle of coupling resonance wavelengths into the ring waveguide which is the base for optical filtering. In case of a single ring resonator which is not discussed here, it could be used as all pass filters in that case with critical coupling, there will be no transmission on resonance. Single ring resonator also works as an add-drop by filter transmitting the resonance wavelength to the drop port. Unequal couplers could affect the performance of the system. So, different ring resonator configuration can be used to design an optical filter for specific application. It is also possible to design multiple ring resonator based optical sensor using surface plasmon resonance technique as the technique was used in [28] in case of optical fiber.

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