DESIGNING AN ULTRA COMPACT TRIPLEXER BASED ON TWO STAGGERED RING RESONATORS USING SILICON WAVEGUIDES

THIẾT KẾ BỘ TRIPLEXER CỰC NHỎ DỰA TRÊN HAI BỘ CỘNG HƯỞNG VÒNG PHÂN TẦNG SỬ DỤNG ỐNG DẪN SÓNG SILICON

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Abstract - An ultra-compact triplexer is designed by utilizing two staggered ring resonators that coupled with directional couplers that based on submicron silicon on insulator (SOI) optical rib waveguides. Firstly, a ring waveguide is designed to separate the wavelength 1490 nm in its drop port. A second ring resonator are utilized for separating the wavelength 1310 nm in drop port and the wavelength 1550 nm in through port . The total size of the present triplexer is only 11.5 µm×8.8µm. Numerical simulations with Finite Differential Time Domain (FDTD) method and effective index method (EIM) are used for design and optimization the operation of the triplexer.

Key words - triplexer; ring resonator; directional coupler; SOI waveguide; FDTD

Tóm tắt - Một triplexer (bộ tách ghép ba bước sóng) kích cỡ cực nhỏ được thiết kế bằng cách sử dụng hai vòng cộng hưởng phân tầng mà được ghép với các bộ ghép trực tiếp trên các ống dẫn sóng cỡ micron. Các ống dẫn sóng dạng sườn được sử dụng vật liệu silic trên nền silic ô xít (SOI). Đầu tiên, bộ cộng hưởng vòng được thiết kế để tách bước sóng 1490 nm xuống cổng rẽ. Một bộ cổng hưởng thứ hai được sử dụng để tách bước sóng 1310 nm xuống cổng rẽ thứ hai và bước sóng 1550 nm được dẫn tới cổng ra thẳng. Kích cỡ tổng cộng của triplexer chỉ vào khoảng 11.5 µm×8.8µm. Mô phỏng số với phương pháp sai phân hữu hạn miền thời gian (FDTD) được kết hợp với phương pháp hệ số hiệu dụng cho thiết kế, đánh giá hiệu năng và tối ưu hóa hoạt động của bộ tripexer.

Từ khóa - triplexer; cộng hưởng vòng; bộ ghép trực tiếp; ống dẫn sóng SOI; FDTD

1. Introduction

Triplexer plays a very important role in a fiber-to-the-home (FTTH) system. According to ITU G.983 recommendation, three wavelengths are utilized commonly to be 1310, 1490 and 1550 nm, for upstream digital, downstream digital and downstream analog channels, respectively. There are some types of triplexers. One is to cascade filters such as thin film filters [1] but this type has a drawback is difficult to integrate with other optical device so it is expensive. Two is to use gratings e.g. arrayed waveguide grating (AWR) [2] and Bragg [3] grating but their size is quite large. The other types are either constructed on MMI coupler technique [4] or used planar lightwave circuits (PLCs) such as photonic crystals [5] or silicon rib waveguide [6]. In there, silicon waveguide is a promising solution due to some its advantages such as high contrast refractive index allows for high confinement of light also high compactness structure with ultra-sharp bending. Moreover, it is very adaptive with CMOS technology [7] thus making it cheaper than the others.

Recently, some ring resonators based structures using silicon waveguide have been proposed, such as WDM filter [8], modulator [9], all optical switching, etc. Ring or disk resonators support traveling wave resonant modes. By side coupling to a signal bus, a single ring may completely extract a particular wavelength. The communications window of WDM filters such as the triplexer supported by erbium amplifiers is 20 nm. Rings with a free - spectra range (FSR) larger than this would require a radius of 5 µm or less [8]. Ring resonator based on silicon waveguide with low loss, high quality factor and small radius only 1.5 µm has been fabricated successfully [10].

In this paper, we present a novel structure for ultra-compact triplexer by using two staggered ring resonators that are coupled with straight directional couplers based on submicron waveguides. The proposed triplexer composes the first ring resonator for separating the wavelength 1490 nm in a drop port and the second ring resonator to separate subsequently two wavelengths of 1310 nm and 1550 nm in its drop and through ports respectively. Due to FDTD is most potential numerical simulation method for ring resonator based structures, so we used the FDTD method for design and optimization of proposed triplexer.

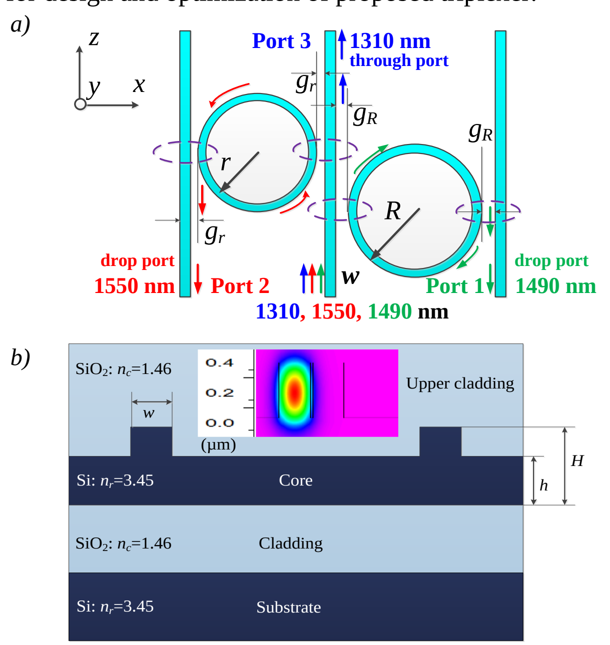

Fig 1. *Proposed schematic of the triplexer based silicon waveguide. a) Top-view. b) Cross-section and fundamental mode of input waveguide.*

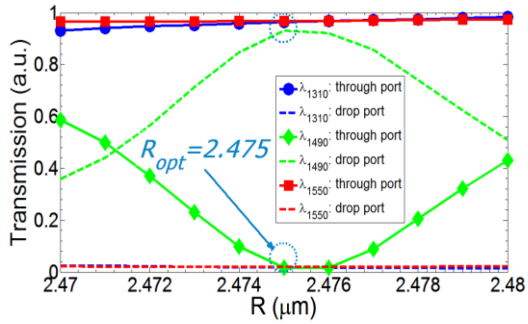

Fig 2. *FDTD simulation for the transmission characteristic of the first ring resonator is a function of radius R.*

2. Design and Optimization

Fig. 1 shows the configuration of the proposed triplexer is based on submicron silicon waveguides. Those submicron silicon waveguides is made by silicon on silica with upper cladding of silica. Refractive index of silicon core layer is n_r=3.45 and silica cladding layer is n_c=1.46. By using the Sell Meier model, we can get that the refractive index difference of silicon core layer between wavelengths 1310 nm and 1550 nm is $\Delta n \approx 0.025$. Such difference is very small so we could be negligible in this design. Hence, in this design, we can consider the refractive index of silicon as a constant. In this design, the triplexer is designed for on operation of TE mode. The width w of the ring resonator and single mode waveguides is in the range from 160 nm to 560 nm for satisfying the single mode condition. In this design, we choose w=360 nm. By using the beam propagation method (BPM) simulation, we found the total thickness of silicon guiding layer H=0.4 µm and the slab height h = 32 nm so that the optical field can be achieved maximally when propagating into the waveguides. Finite element method (FEM) simulation for fundamental mode is shown in the Fig. 1b). The proposed structure can be fabricated by using currently electron beam (EBeam) lithography technology, such as 193 nm deep ultra violet (DUV) EBeam lithography technology.

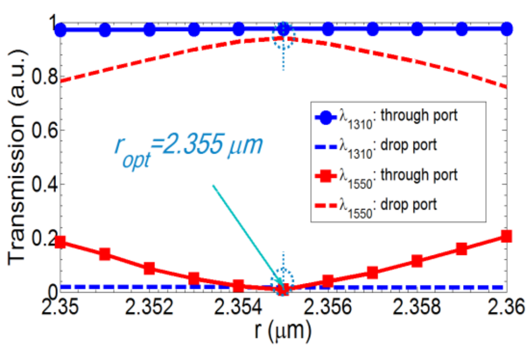

Fig 3. *FDTD simulation for the transmission characteristic of the second ring resonator as a function of radius r varies.*

Basic operation principle of the proposed triplexer is present in Fig. 1. There are two sections. The first section includes a ring resonator and two straight waveguides that they are coupled with the ring resonator. The first ring resonator is designed to resonate with the wavelength of 1490 nm, while wavelengths of 1310 nm and 1550 nm are passed through it. This aims to separate the wavelength 1490 nm to port 1 as seen on Fig. 1. The second section aims to separate wavelengths of 1310 nm and 1550 nm subsequently to two remaining ports. The design purpose of the second ring resonator is to separate the wavelength of 1550 nm to drop port (port 2) and the wavelength of 1310 nm to through port (port 3) as seen on Fig. 1. Hence, the second section composes a ring resonator are both coupled commonly bus and staggered with the first ring resonator so that the optical signal when traveling the through port of the first ring resonator will resonate with the wavelength of 1550 nm and pass through the wavelength of 1310 nm as seen on Fig. 1.

As a presented preliminary, firstly we design a ring resonator for separating the wavelength of 1490 nm. The gap g_r between straight waveguides and ring resonator is chosen as g_R=35 nm. The radius R of the first ring resonator is designed so that the first ring resonates with the wavelength of 1490 nm and it doesn't resonate with wavelengths of 1310 nm and 1550 nm. The resonance condition must satisfy $R=p\lambda_{1490nm}/2\pi n_{eff}$, where p is a positive integer and n_{eff} is effective refractive index of the waveguide. FDTD simulation method has been used in designing and optimizing the ring resonator which based on high refractive index contrast nanowire waveguides, the accuracy of the FDTD simulation for those waveguides is high enough if the grid sizes are small enough. Based on the FDTD simulation, we find that to obtain the full coupling and mode coupling coefficient between the straight waveguide and ring resonator waveguide maximally when the gap g_R was 35 nm, the radius R should be in the range from 2 µm to 3 µm. Then, by changing the value of radius R of the ring resonator following three wavelengths of 1310 nm, 1490 nm and 1550 nm in the selected range to find out an optimal value which must satisfy the conditions: the outputs power at drop port (λ=1490 nm) and through port (λ=1310 nm and 1550 nm) are maximal. Result, we chose the optimal value of radius to be R_{opt} =2.475 µm (see the marked point in Fig. 2). The center of the first ring resonator is placed at the position of 3.2 µm in the z-propagation direction.

Next, we consider a second ring resonator for separating the remaining wavelengths of 1550 nm and 1310 nm. The gap g_r between straight waveguides and ring resonator is chosen by FDTD simulation as g_r=22 nm so that the resonance in the second ring resonator is maximal. The radius r of the second ring resonator is designed so that the wavelength of 1550 nm is resonated in the second ring and the wavelength of 1310 nm is propagated pass through over commonly bus of two ring resonators. The resonance condition must satisfy to be: $r=q\lambda_{1550nm}/2\pi n_{eff}$, where q is a positive integer and n_{eff} is effective refractive index of the waveguide. Based on the FDTD simulation, we find that to obtain the full coupling when the gap g_r was 22 nm, the radius r should be in the range from 2 µm to 2.5 µm. Then we reuse the FDTD simulation by changing the value of radius r of the second ring resonator following three wavelengths of 1310 nm and 1550 nm in the selected range to find out an optimal value which must satisfy the conditions: the outputs power at drop port (λ=1550 nm) and through port (λ=1310 nm) are maximal. Finally, we chose the optimal value of radius to be r_{opt} =2.355 µm (see the marked point in Fig. 3). The center of the second ring resonator is placed at the position of 5.4 µm in the z-propagation direction. We choose the length of the straight-waveguide as 8.8 µm which is proper for operation of the device. Result, the total size of the proposed triplexer is very small only about 11.5µm × 8.8 µm.

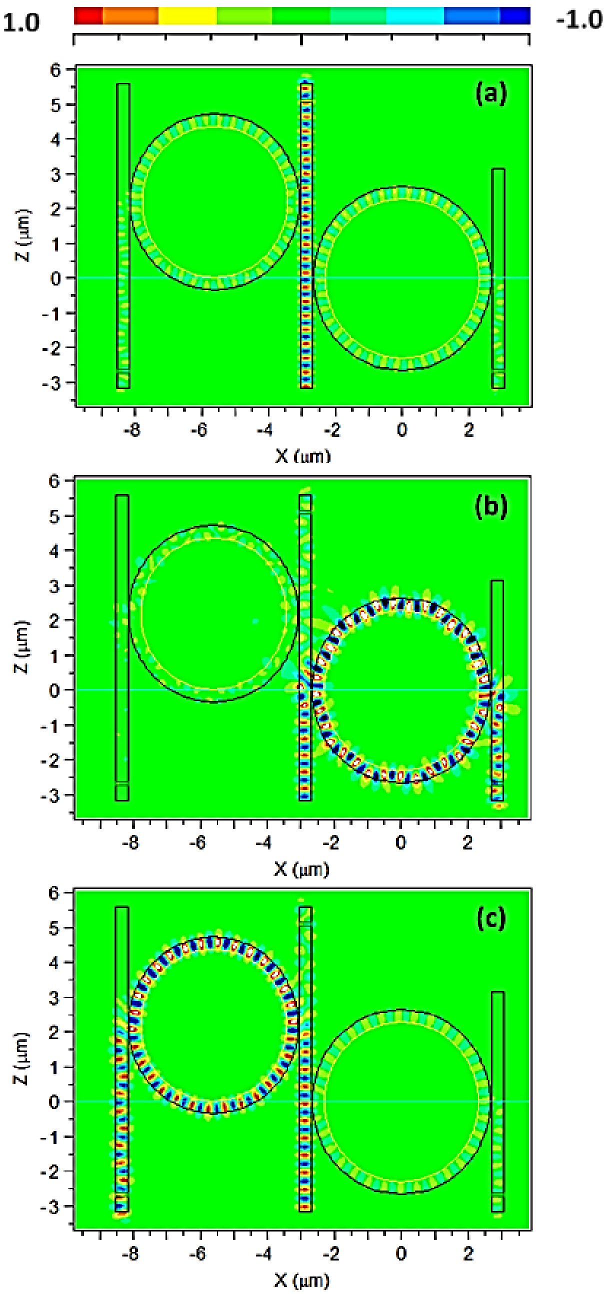

Fig 4. FDTD simulation for electric field distribution in the triplexer for: a) 1310 nm, b) 1490nm and c) 1550 nm.

***Table 1**. Output powers (normalized to the input power) of three output ports of the proposed triplexer at three wavelengths.*

Wavelength (nm)	Port1 (dB)	Port2 (dB)	Port3 (dB)
1310	-17.48	-17.62	-0.2
1490	-0.22	-17.66	-16.56
1550	-17	-0.68	-17.7

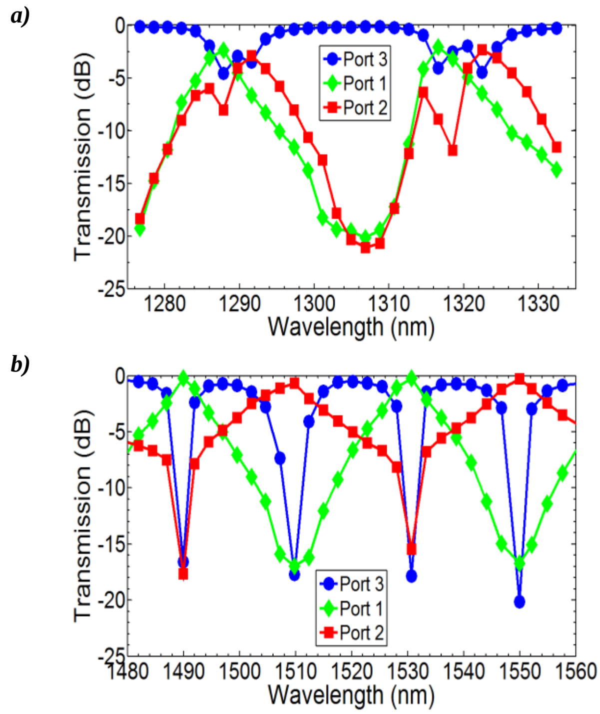

Fig 5. Wavelength responses of the proposed triplexer at three ports for thee wavelengths. a) 1310 nm band. b) 1490 nm and 1550 nm bands.

3. Simulation Results and Discussion

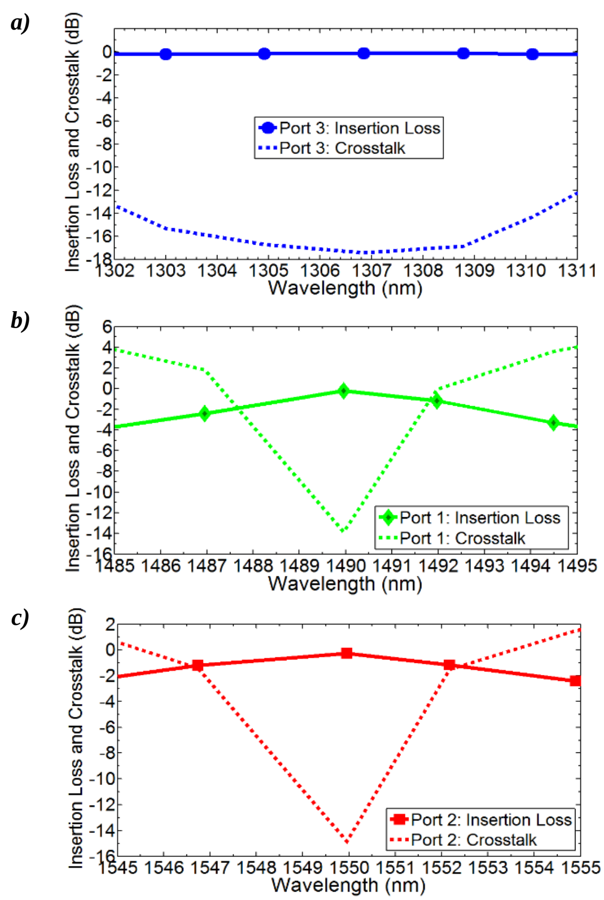

Fig 6. Wavelength dependencies of insertion loss and crosstalk of the triplexer for: a) 1310 nm band, b) 1490 nm band and c) 1550 nm band.

By using the FDTD method, we do simulate the optical signal propagation for all ports of the triplexer. Fig. 4 presented electric field pattern distribution by FDTD simulation in the triplexer at three wavelengths of 1310 nm, 1490 nm and 1550 nm respectively. The output powers at different output ports (normalized to the input power) are shown on Table I.

Fig. 5 shows the wavelength response of the proposed triplexer. Because of the high index contrast and smooth bending of ring resonators, bending loss could be negligible in this design [8]. From simulation data, the most importance performance parameters of the triplexer based on ring resonators such as free spatial range (*FSR*), 3-dB bandwidth of the resonance ($\Delta\lambda$) and quality factor (Q) etc. can be easy to obtain. For example, from Fig. 5, *FSR* parameters of port1and port2 are about 40 and 40 nm respectively (due to wavelengths of 1490 nm and 1550 nm are dropped into port1 and port2 respectively). The 3-dB bandwidth of the resonance of port1 and port2 are corresponding to 3.8 and 5.4 nm. These correspond to quality factors of 392.1 and 287, defined as $Q=\lambda/\Delta\lambda$. These quality factors are suitable in comparison with an existing triplexer [5].

For a triplexer, the most important performances are the insertion loss (I.L) and the crosstalk (Cr.T), these are defined as follows:

$$\mathrm{I.L} = 10\log\left(\frac{P_d}{P_{in}}\right) \quad (1)$$

$$\mathrm{Cr.T} = 10\log\left(\frac{P_d}{\sum P_u}\right) \quad (2)$$

Where P_{in} is the power in the input waveguide, P_d and ΣP_u are corresponding to the power from the desirable output waveguide and the total power from undesirable output waveguides.

Finally, Fig. 6 shows wavelength dependencies of insertion loss and crosstalk of the triplexer. Simulation data to show that at the level of crosstalk below -12 dB, bandwidths of port3 (1310 nm band), port1 (1490 nm band) and port2 (1550 nm band) are about 9.6 nm (from 1301.4 nm to 1311 nm), 0.62 nm (from 1489.6 nm to 1490.22 nm) and 1.14 nm (from 1549.28 nm to 1550.42 nm), respectively. These bandwidths of output ports of the proposed triplexer are also corresponding to the variation of insertion losses of 0.3 dB, 0.5 dB and 0.5 dB respectively. The worst case of the bandwidths is the case of port1. This is explained by the resonance performance of the ring resonator for the wavelength of 1490 nm is worst. However, such performances are quite good for application of the triplexer. Especially, simulation results showed that the proposed triplexer has low loss. Nevertheless the optical performances of the proposed triplexer are better than some published ones realized by planar lightwave circuits in comparison with insertion loss also about crosstalk [4], [6], [7]. Another highlight importance is because of very small size of the proposed triplexer in comparison with recent published ones, [5], [6]. Our triplexer has the total size only $11.5\times8.8\ \mu m^2$, it is clearly very appropriate for compactness photonics integrated circuits.

4. Conclusion

We have introduced a compact triplexer by using two staggered resonators which coupled directionally with straight waveguides and it is based on silicon rib waveguides. The ring resonators are used for demultiplexing the wavelengths of 1490 nm and 1550 nm. Insertion losses at three output ports of three wavelengths are below 0.7 dB so our triplexer has low loss. Simulation was implemented by using the FDTD to show that the triplexer has good performances. The total size of the device is much smaller than some existing triplexers.

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