# Active Microring Based Tunable Optical Power Splitters

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## Abstract

In this paper we propose a set of novel tunable optical power splitters based on active microring resonators. They work by operating ring resonators in the transient zone between full resonance and off-resonance states for a specific wavelength. We can achieve different split ratios by either varying the bias voltage, or by selectively enabling a given resonator with a specific split ratio among an array of ring resonators. We take 500 ps to tune the resonator, which is at least 10X better that competing designs. Its split ratio varies from 0.4 to 1.8 for an applied voltage range of 0-5V.

*Keywords:* Tunable splitters, ring resonators, electro-optic modulation, transient zone operation

## 1. Introduction

Optical networking is posed to be a disruptive technology in the future. However, before its commercial adoption, it is necessary for the research community to look at some of its important shortcomings such as high static power dissipation. Static power dissipation is defined as the power that is wasted in the optical network, and is not used to transmit any messages. Over the past 5 years, this has been an area of active research [1, 2, 3]. The standard approach adopted by all the proposals is to predict or ascertain network usage in the near future, and configure the off-chip laser and associated power splitters in the power delivery network to provide power that is just enough to achieve reliable communication.

In most processor architectures that use an optical network, a structure called a *power waveguide* is used to deliver power to all the optical stations (transmitters). The power waveguide is typically a serpentine [4] shaped waveguide that passes through all the stations. It is not uncommon to use a tree shaped power waveguide also (see [1]). The basic principle is the same. Each station diverts (or splits) a part of the power in the power waveguide for its own use. This is done using power splitters such as Y junctions [4] or directional couplers. The split ratio for such splitters is a constant. Peter et al. [5] have shown that this approach is extremely inefficient in terms of optical power consumption because a lot of stations are provided power even when they do not need it since they are not transmitting any message on the network. It is instead a much better idea to transfer just enough power to stations that need to transmit a message. Peter et al. [5] have already proposed an optimal algorithm to compute the split ratios of splitters in the power waveguide for such a setting. However, they assume optical power splitters where the split ratio is *tunable* and can be tuned (or reconfigured) at periodic intervals of time.

In their work they did not propose a splitter whose split ratio is tunable. Instead, they cited prior work that uses MMI based power splitters that take 6 ns to tune. While the splitters are reconfiguring (tuning), they cannot be used. Other references [1, 2] have also used MMI based power splitters for optimally delivering power on the power waveguide. Some of our experiments, as well as by others [1, 6] indicate that we need splitters that have much lower reconfiguration times for creating power efficient optical networks. The tuning time should be preferably less than 1 ns, or even 500 ps. We provide a solution for this problem in this paper, and propose a novel power splitter based on ring resonators that meets these specifications.

Note that it is not a broadband splitter, it is instead a single frequency power splitter. Our modified ring resonator sends a fraction of the power along the through port, and a fraction of the power along the drop port (see Figure 1 for the details of a ring resonator). Optical networks typically send signals at many different wavelengths at once (dense wavelength division multiplexing(DWDM)). We can use the small area-efficient device proposed by Levy et al. [7] to generate up to 64 different wavelengths from the monochromatic optical signal sourced from the power waveguide at each transmitter inside the chip. The transmitter can then use these wavelengths to transmit a message using DWDM. There are many other ways of generating light at multiple frequencies for DWDM based communication. They are however out of the scope of this paper.

Now in specific, we provide three solutions to the problem of creating a tunable power splitter. The first solution involves changing the bias voltage of a ring resonator that operates in *partial resonance*. A typical add-drop ring resonator has two useful states: full resonance (almost all the power passes through the drop port), and off resonance (all the power passes via the through port). A partially resonant state is in between when a fraction of the power passes through the drop port, and another fraction passes via the through port. Now, by changing the bias voltage, we change the carrier concentration, and thus the effective refractive index of the circular waveguide in the ring. We show that by using this technique, we can change the ratio of power transmitted along the through and drop ports. We collect detailed device simulation results using Lumerical [8, 9] simulations, and demonstrate that we can vary the split ratio between 0.4 and 1.8 within a time limit of 500 ps.

We outline two other solutions, which are equally fast, albeit simpler at the cost of area. Both of them use an array of ring resonators with different configurations. The first solution uses an array of resonators of different sizes, where each of them is in partial resonance with a different split ratio. We can selectively enable (bring to partial resonance) one of them by applying a bias voltage, and disable (off resonance) the rest by setting the bias voltage to 0. The split ratio of the array of resonators is now the same as that of the resonator that is *enabled*. Similarly, to achieve a different split ratio, we can enable another resonator, and disable the rest in the array. Likewise, we propose another solution that uses different resonators pre-heated to different temperatures to achieve partial resonance (details in Section 2.3).

The contributions of our work are as follows:

1. The idea of using ring resonators as tunable power splitters by running them at partial resonance.
2. The design and detailed evaluation of electrically tunable ring resonators.
3. Two alternative solutions for creating tunable power splitters using an array of resonators.

## 2. Fast Tunable Splitters

### *2.1. Physics of Ring Resonators*

A ring resonator is typically designed to resonate at a certain frequency. Here, *resonance* or full-resonance is defined as a situation where almost all the power passes from the input port to the drop port. Likewise, an off-resonance state indicates a situation, where almost all the power (barring losses in the waveguides) passes from the input port to the through port. As we have defined in the introduction, a partially resonant state is in between when the ring resonator functions as a splitter.

The resonance condition is given by the Drude model.

$$\lambda_m = 2\pi R n_{eff}/m \tag{1}$$

Here, $\lambda_m$ is the resonant wavelength, $m$ is the mode (integer), $R$ is the radius of the ring, and $n_{eff}$ is the effective refractive index. The optical path length is defined as $2\pi R n_{eff}$. It should be an integral multiple of the resonant wavelength for resonance to occur. From Equation 1, we can easily derive the following formula:

$$\frac{\Delta\lambda_m}{\lambda_m} = \frac{\Delta n_{eff}}{n_{eff}} \tag{2}$$

The operator, $\Delta$, denotes a change or difference. $\Delta(\lambda_m)$ is the change in $\lambda_m$, and $\Delta(n_{eff})$ is the change in the effective refractive index ($n_{eff}$). From this equation, we observe that as the effective refractive index changes, the resonant wavelength will also change. An interesting property of a ring resonator is that for small values of $\Delta(n_{eff})$ the ring resonator does not go to an off-resonace state. Instead, it is somewhere between full and off-resonance, and works as a power splitter. A fraction of the power is sent along the through port, and a fraction of the power is sent along the drop port (see [10] for the equations). The crucial insight here is that, if we can make **make minor changes to $n_{eff}$**, then we can operate the ring resonator in a partially resonant state.

Hence, to make a resonator work like a splitter, it is necessary to run it between its on and off states. The behavior of the resonator that is slightly off-resonance is captured by the $Q$ factor. A resonator, with a high Q factor stops acting like a splitter for very small values of $\Delta n_{eff}$. Conversely, a resonator with a low Q factor acts like a splitter for a much larger range of $\Delta n_{eff}$. There are several ways in which we can change the effective refractive index or the optical path length ($2\pi R n_{eff}$). We can either change the carrier concentration by applying an electric field, change the radius $R$, or change the temperature. The temperature affects the carrier concentration. Let us look at these three strategies in turn.

### *2.2. Electrically Tunable Ring Resonator*

If we can vary the voltage applied to a part of the ring, we can alter the refractive index, and also the optical path length. If the optical path length is close to the resonant wavelength, the resonator will work like a splitter. Most nanophotonic ring resonators today use modulation voltages in the range of 1-3V [11]. Bogaerts et al. [10] propose electrically modulated silicon microring resonators, its properties, parameters that influence the operation and its applications. They discuss about shifting a resonator from resonant state to the non-resonant state by applying an electric field. But they have not studied the effect of applying a voltage to shift the resonator to a transient state between resonant and non-resonant states of the resonator. To use the resonator as a splitter we need a fast DAC (digital to analog converter) that can produce any voltage between 0V and the modulation voltage. We already have commercially available 4-6 bit DACs that can switch at 2-5 GHz, which is enough for our purposes.

#### *2.2.1. Design of an Active Ring Resonator based Splitter*

In order to develop such a microring resonator modulator, modulation of the refractive index of the ring waveguide is carried out by employing several techniques. The most commonly used technique for fast switching is by actively controlling (i.e. by applying voltage) the carrier concentration in the ring waveguide. In a semiconductor, the carrier concentration has an impact on its refractive index. We employed a p-n junction based structure in the ring waveguide of the resonator and applied a reverse biased voltage to vary the depletion width of the junction (as illustrated in Figure 1). This is arguably a much faster technique compared to other mechanisms such as carrier injection in a p-i-n diode (proposed in [11]), because the movement of the carriers is limited by only its saturation

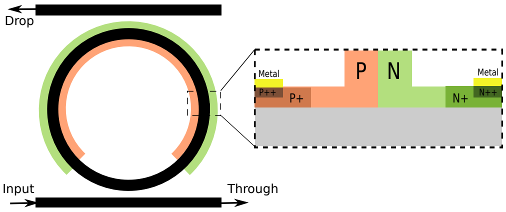

Figure 1: Schematic diagram of an active microring resonator

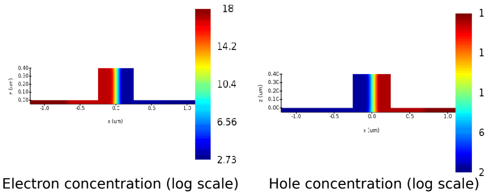

Figure 2: Cross-sectional view showing the charge density profile of the p-n junction in a ring waveguide in a microring resonator modulator

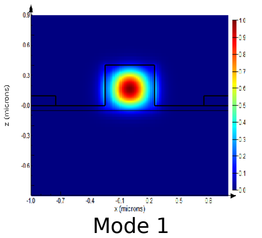

Figure 3: Cross-sectional view of the mode profile, of the mode propagating in the ring waveguide of a microring resonator modulator

velocity and the junction capacitance. Changes in the carrier density have also an effect on the Q factor of the ring as it influences the absorption.

We designed a ring resonator (slab thickness: 0.9 $\mu$m, rib thickness: 0.22$\mu$m, midpoint implant: 0, implant width: 0.22$\mu$m, radius: 9$\mu$m, width: 0.5$\mu$m), and simulated it with a reverse biased p-n junction device. A device solver, (Lumerical DEVICE 4.5) was used to obtain the carrier concentration profiles. We applied a bias voltage across the ring shaped optical waveguide in order to control its carrier concentration. The spatial distribution of the carrier concentration in the ring waveguide of the ring resonator based modulator is shown in Figure 2.

The spatial charge distribution data was imported into the mode solver (Lumerical MODE Solutions 7.5) for obtaining the loss in the waveguide and its effective index as a function of applied bias. Figure 3 shows a cross-sectional view of the mode profile, of the mode propagating in the ring waveguide of a microring resonator modulator. The mode solver was employed to calculate the mode profile and the effective refractive index of the waveguide based on the carrier concentration distribution. As the bias voltage on the p-n junction based optical waveguide changes, the effective refractive index and mode profile change. The effective refractive index and waveguide loss as a function of voltage was subsequently imported to an optical interconnect and circuit modeling software, (Lumerical INTERCONNECT 4.5), which was used to calculate the transmitted and reflected light as a function of the reverse biased voltage applied on the microring resonator.

The designed microring resonator demonstrates a variation in split ratio on the application of a reverse biased voltage at a wavelength of 1546.91nm as shown in Figure 4. The voltage is varied from 0V to 5V to get a split ratio from 1.8 to 0.4. On the application of a voltage, the reverse current through the p-n junction is measured as $3.945 \times 10^{-19} A$. We measured the junction capacitance of the designed resonator as $80.304 fF$ at 5V. The dynamic power is calculated as $2mW$. The leakage power is $1.973 \times 10^{-18} W$, which is a thousandth of a femtowatt throughout the region of operation (0-5V) with a variance of at the most 10%. Even if we have a thousand such ring resonators on a chip, the leakage power dissipation will be negligible (a few femtowatts).

The important point to note is that we do have fair split ratios even at lower voltages. Figure 6 shows the resonant wavelength shift at the through and drop ports with respect to change in voltage.

A DAC can be employed to generate the tuning voltage for this microring resonator [12, 13]. Some examples of DACs are as follows. DAC1653Q/DAC1658Q [12] is a quad 16-bit DAC, which can operate at 2GHz. Semtech has announced an ultra-high speed DAC [13] for 32nm SOI technology for high performance SoCs, which can work at 64 GHz. Given the fact that ring resonators represent a predominantly capacitive load, we can use such DACs to modulate the bias voltage at processor speeds ($\approx$ 2 GHz). Ring resonators were found to optically stabilize in less than 100 ps in our experiments, and in less than 450 ps in [11]. Thus, the total tuning time is at the most limited to 500 ps (assuming a 2GHz DAC). We thus have an ultra-fast ring resonator based tunable splitter.

#### *2.2.2. Robustness of the Design*

In Figure 5 we plot the deviation in split ratio as a function of the number of bits required by the DAC. For example, if we consider a 4-bit DAC, we have 16 possible voltages that correspond to 16 different split ratios. If we needed any split ratio in between two consecutive split ratios $r_1$ and $r_2$, then the maximum error in the split ratio is limited to $(r_2 - r_1)/2$. We consider all such maximum errors across consecutive pairs of voltages, and plot the average and maximum values (across all the pairs). We observe from Figure 5 that the error in the split ratio is 0.1 on an average and can increase up to 0.25. For most practical designs, we might need DACs with more bits (5 or 6). With 6 bits, the mean error is much lower (0.01), and the maximum error is 0.03. This is a feasible operating point, and thus 6-bit DACs can be used to realize such splitters. The error is almost negligible, when we use a 8-bit DAC.

### *2.3. Alternative Solutions using an Array of Resonators*

#### *2.3.1. Resonators of Different Sizes*

We use a set of high Q ring resonators of different sizes as shown in Figure 7. Each resonator has a slightly different inner radius. All of them function as splitters when they are modulated (voltage applied across two parts of the ring), albeit with different split ratios. We enable one out of $N$ resonators and the enabled one works as a splitter.

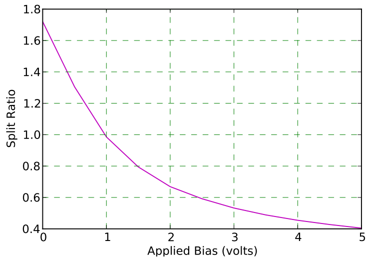

Figure 4: Split ratio of a microring resonator as a function of applied bias

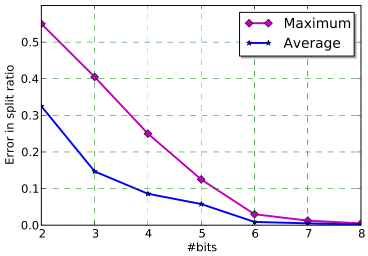

Figure 5: Error in split ratio

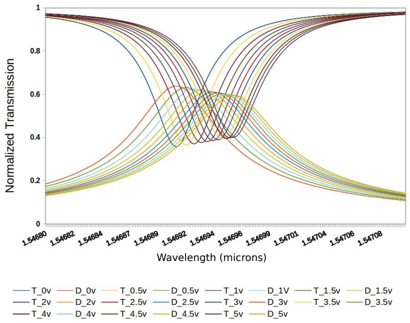

Figure 6: Shift in resonance wavelength in the through port and drop port with a change in applied voltage ($T$: Through port and $D$: Drop port)

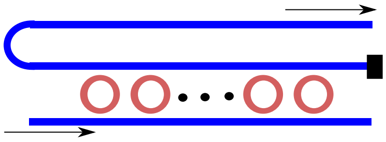

Figure 7: Schematic showing a 16-step tunable splitter

There is no extra effort required in fabricating each resonator. The resonators just need to have slightly varying dimensions. Since resonators can already work at multi GHz speeds, the ensemble as a whole will also work at that speed. The critical path in terms of timing is to turn off a set of resonators and to simultaneously turn a resonator on. This takes less than 100 ps. If we have 16 such resonators, we have a tunable power splitter with 16 steps.

### *2.3.2. Resonators with Different Temperatures*

The objective is to have resonators at different pre-set temperatures. The rate of change of the refractive index with temperature is $1.86{\times}10^{-4}/K$. If we consider a 20K temperature tuning window, then we can change the refractive index by 0.003. We can use the same technique as shown in Figure 7 to realize a 16-step tunable splitter. Microheaters for ring resonators are already used in optical systems to maintain a steady temperature. If the separation(center to center) between two resonators is more than 4 $\mu$m, then the thermal coupling is very low because point sources of heat have a very localized effect [14, 15, 16].

Such schemes are no doubt simpler. Microheaters are already used in all optical systems that use ring resonators for thermal stabilization (see [16] for a very efficient design), and fabricating micron size resonators with different radii is also not difficult. The only shortcoming as compared to electrically tunable splitters is the additional area. To realize 64 split ratios, we need a standard 6 bit DAC for electrically tunable resonators, whereas for these designs we need 64 resonators with different configurations. This is not area efficient. These alternative solutions are better when we need fewer split ratios.

## 3. Conclusion

In this paper we showed the design of a high speed microring resonator, which can be used as an ultra-fast optical power splitter. The main insight that we used is that we can run such splitters in a partially resonant state, which is a transient state between full resonance and no resonance. We showed a fully functioning design where we vary the electrical bias voltage to change the carrier concentration, and thus the effective refractive index and optical path length. This helps us operate the resonator at different levels of partial resonance, and it thus works as a power splitter. We propose two alternative designs that may support fewer split ratios but are simpler to design. They use an array of resonators with either different radii, or different pre-set temperatures. The speed of all our resonators are limited by the fastest DACs that are available. Currently, our reconfiguration time (tuning speed) is limited to 500 ps. We expect it to rise in the future, as DACs get faster.

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