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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 10 × better that competing designs. Its split ratio varies from 0.4 to 1.8 for an applied voltage range of 0–5 V.

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 [4–6]. 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 [7] shaped waveguide that passes through all the stations. It is not uncommon to use a tree shaped power waveguide also (see [4]). 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 [7] or directional couplers. The split ratio for such splitters is a constant. Peter and Sarangi [8] 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 and Sarangi [8] 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 [4,5] have also used MMI based power splitters for optimally delivering power on the power waveguide. Some of our experiments, as well as by others [4,9], 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 Fig. 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. [3] 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

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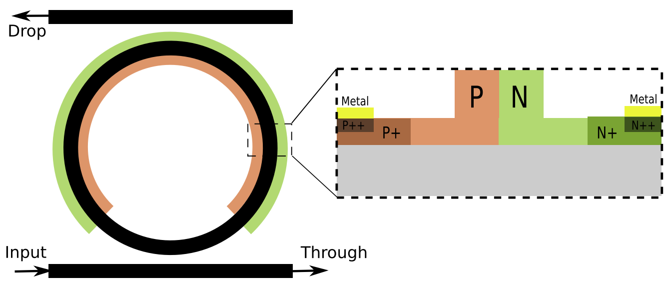

Fig. 1. Schematic diagram of an active microring resonator.

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 [10,11] 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, λ_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 Eq. (1), we can easily derive the following formula:

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

The operator Δ denotes a change or difference. $\Delta(\lambda_m)$ is the change in λ_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-resonance 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 [12] for the equations). The crucial insight here is that, if we can *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 Δn_{eff}. Conversely, a resonator with a low Q factor acts like a splitter for a much larger range of Δn_{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 1–3 V [13]. Bogaerts et al. [12] propose electrically modulated silicon microring resonators, its properties, parameters that influence the operation and its applications. They discuss about shifting a resonator from the 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 0 V 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 based 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