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Invited Paper

Automated Tuning and Channel Selection for Cascaded Micro-ring Resonators

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ABSTRACT

As bandwidth requirements and integration of photonic components in computing systems increase, the optical micro-ring resonator are becoming an important building block for dense, high-bandwidth interconnects. Ring resonators are small in size and can operate at data rates up to 60Gb/s NRZ,[1] making them well-suited for integrating many rings operating at different wavelengths into a single device. These devices are a promising solution for complex interconnected systems, such as chip-to-chip interconnects.[2] However, using these rings can be challenging as they are sensitive to fabrication and temperature variations and need constant tuning to lock them to their assigned optical wavelengths.[3] This tuning is commonly done by inserting embedded heaters in or above the ring. Existing techniques that tune the rings by the optical power coupled into the rings require extensive characterization and spectrum analysis, or out-of-band signalling, to account for rings drifting across optical channels and fabrication variations. In this work, we use four cascaded micro-rings implemented in a silicon photonic device operating in the C-band. Each ring taps a single wavelength from a bus waveguide. The remaining light in the bus waveguide is then fed into a photodiode, which is used to monitor the tuning of all rings. We show an algorithm that, based only on information about the design of the chip, tunes the rings to the exact desired optical channel. With this algorithm the use of more complex techniques to directly measure a ring's coupled wavelength can be avoided, reducing system complexity.

Keywords: Silicon Photonics, SiP, micro-ring resonators, DWDM, thermal stabilization, wavelength locking

1. INTRODUCTION

Dense Wavelength Division Multiplexing (DWDM) is used in many types of systems to achieve the increasing bandwidth requirements of computing systems. To implement low cost, energy efficient, DWDM links, the use of micro-ring resonators in integrated Silicon Photonics (SiP) platforms is very promising. Micro-rings are compact and have been shown to modulate data at up to 60Gb/s NRZ[1] and 112Gb/s PAM4.[4] Because micro-rings are wavelength selective, they can also function as a wavelength selective filter. When a number of micro-rings are cascaded along a bus waveguide, they can combine the function of modulator and wavelength demux without requiring additional optical components, making this a useful structure for DWDM modulators and receivers.[5,6] A challenge when using silicon micro-rings is that silicon has a large thermo-optic coefficient,[7] and small changes in ambient temperature cause a ring's resonance frequency to shift significantly. This is compounded by small manufacturing variations resulting in small differences in resonance frequencies between copies of the same micro-ring. A resonance shift due to a change in ambient temperature of 0.1nm/°C will move the resonance frequency by 6nm over a range of 25-85°C. In case of a system using the standard ITU grid,[8] channels are spaced by 0.8nm (100GHz), so this 6nm shift can cause rings to shift across multiple channels.

To solve this, much work has been done on locking rings to a desired wavelength and maintaining that lock. This is typically done using micro-heaters placed in or near the ring.[9–11] The ring can be locked to an optical signal by sensing the power coupled into the ring and employing a feedback to loop to either maximize or minimize that power, depending on the desired configuration. Many implementations for sensing the optical power coupled into a micro-ring exist, each with pros and cons. The simplest implementation of this control loop is to tap some power from the ring and measure it using a photo-diode. Many other more advanced techniques exist. Some examples rely on the photoconductance of doped heaters,[12] or use a single optical power tap to measure the

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response of multiple cascaded rings.[13] The techniques reduce the number of electrical connections compared to the simplest case and/or the number of analog-to-digital converters (ADCs). None of the mentioned techniques, however, can completely solve the problem of locking rings to a specific desired wavelength in a DWDM scenario. Because the unbiased 'starting' resonant frequency is unknown, and the exact wavelength rings are tuned to is not measured, it is difficult to distinguish different channels from each other. As a result, rings can be tuned to the wrong channels. In some systems, the receiver of the optical signals can decode the channel it is receiving. From there the system can deduce which channel each ring is tuned to and correct this, if necessary. This is, however, not always possible. For example, when designing a pluggable optical transceiver that needs to work with a wide range of other devices in a network, of which the transceiver has no knowledge or control.

In this work, we demonstrate a fully automatic algorithm to map micro-ring resonances to specific wavelengths without requiring intensive characterization of individual devices, exact frequency measurements, and only minimal external information. This algorithm works on the basis of detecting when rings are locked to the same wavelength and builds a list of control voltages that map to the same wavelengths. By combining this list with information about the design of the rings, such as their designed size or the number of wavelengths in the system, the algorithm can place each ring at an exact wavelength channel. After each ring is placed at the desired wavelength channel, previously reported techniques can be used to keep them locked to their respective channels.

2. APPLICATION SYSTEMS

In telecommunication optical networks various techniques exist for out-of-band signalling and channel identification, which can be used to ensure network components are tuned to their correct optical channel. This also requires some form of network management to tell all components how to interpret this out-of-band signalling. In contrast, optical transceivers employing coarse wavelength division multiplexing (CWDM) used in data centers use such large channel spacing that optical wavelengths can drift across multiple nanometers without issue. One advantage of allowing for such a large wavelength tolerance is that the transceivers do not need to communicate with other network components to establish a reliable connection, as opposed to the telecommunication systems. The algorithm we are presenting in this work is intended for use in systems where it is desirable to have minimal knowledge of the other equipment in the system, like the transceivers in data centers, but where the required number of channels is so high that it is not possible to allow for the wide channel spacing. Using this algorithm we can also remove any extra components that would be needed for out-of-band signalling. The algorithm allows a system that consists of a number of cascaded micro-ring resonators to tune to specific channels, by only measuring the power coupled into the rings, and tuning the rings. For this it only needs to know how many optical channels are launched into the device, and the sizes each ring is designed to operate at. Its basic principle is that it finds all channels each ring can tune to, and to detect when two adjacent rings are tuned to the same channel. With adjacent rings we do not mean rings physically placed next to each other, but two rings that are designed to operate at adjacent channels. To detect when two adjacent rings are tuned to the same channel, they need to be close enough, or be able to tune across a large enough range. The easiest way to ensure this, is to make sure rings can tune across a large enough range so that any fabrication variation will not result in two adjacent ring's resonances being so far apart they cannot tune to the same optical channel.

One challenge that needs to be resolved is that a micro-ring has many resonances. While a ring is set to the largest wavelength channel and is then tuned farther, it can lock to the smallest wavelength with the next resonance. This situation can be difficult to distinguish from tuning between two channels using the same wavelength. To reliably determine which of these situations is happening, the wavelengths need to be such that the amount of resonance shift required to go from the last to the first channel, needs to be significantly larger than the spacing between channels. By tuning over at least three channels, the algorithm can measure the difference in tuning power required to move between channels and if one of the two shifts is significantly larger than the other, that one is the switch from last to first channel. To account for fabrication variations, it the accuracy of this is improved by tuning over more than three wavelengths, so that the algorithm has data points to do this comparison.

We demonstrate the algorithm using the system schematically shown in Fig. 1. It consists of a bus waveguide and eight cascaded micro-rings that each drop a signal from the bus waveguide to an optical output. Due limited

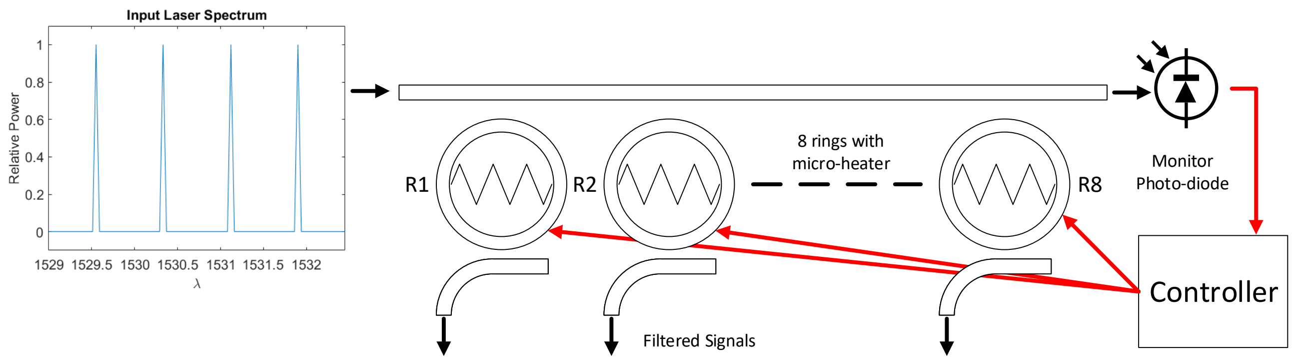


Figure 1: Schematic representation of cascaded micro-rings and controller. Four wavelengths are launched into the bus waveguide. Four of the eight rings are used to couple to the optical signals, while the other four are fixed so that they do not couple any light. All remaining light is coupled into a photodiode for monitoring.

availability of suitable drivers, we use four of the micro-rings. All light that is not dropped by the rings is fed into a photo-diode to monitor the locking status of the rings. The controller can set a voltage across each ring's micro-heater to tune its resonant wavelength. DWDM small form-factor plus (SFP+) transceivers, set to ITU channels 57 (1531.90nm), 58 (1531.12nm), 59 (1530.33), and 60 (1529.55), are used as the light source. The output from the transceivers is muxed together and launched into the device.

To maximize the coupling of light from the bus waveguide into the rings, the controller must minimize the optical power on the photo-diode. To demonstrate the algorithm, four wavelengths and rings are used. Once the controller has found the correct configuration using the algorithm presented in the next section, it can use existing techniques to maintain that configuration.[13]

3. ALGORITHM

The algorithm to lock cascaded rings to specific channels is outlined in Algorithm 1. The version shown is for a receiver system with a single monitor photo-diode like in our system. To find if a ring is locked to a wavelength it looks for a local minimum in received power. For modulator devices the algorithm needs to be modified to find local maximas in modulated power. And when each ring has a its own monitoring diode, the measurement of optical power also needs to be modified slightly and select the correct ring to measure. But the principle of finding wavelengths and overlapping the resonances stays the same.

3.1 Finding Available Wavelengths

The algorithm starts by finding all voltages at which a ring couples to a wavelength(lines 3-5), which it does for each ring separately. Before it searches each ring all rings are detuned. This is done so that the ring being search will be able to see all wavelengths within its tuning range. The result of this search is a list of all voltages, for each ring, that map to some wavelength, and the corresponding change in optical power received P_{diff} by the monitor diode(s). These voltages are denoted $V_{r,i}$, with r being the index of the ring and i the index of the found voltage and wavelength. The first found wavelength for ring r is mapped to $V_{r,1}$, the next to $V_{r,2}$, and so on. The next step is to find which voltages on different rings map to the same wavelengths. The process for this is detailed in Section 3.2. Once the system knows when different rings couple to the same wavelength, it combines this with some information from the design of the system to map each ring voltage to a specific channel. This is explained in Section 3.3.

3.2 Finding Matching Wavelengths

The core of the algorithm is determining at which voltages micro-rings couple to the same optical wavelength. When two rings are set to the same wavelength, the second ring will not couple as much light as it did during the initial search for available wavelengths, because the first ring will already have coupled most of the light on

Algorithm 1 Map Rings Algorithm for cascaded receiver micro-rings

Design Parameters: N_{RINGS} (Number of cascaded rings), ΔV (Voltage step when scanning)

All rings are indexed in order of ascending designed resonance. I.e. R_1 is designed to operate at the lowest wavelength and R_N at the highest. They do not have to be constructed in this order though.

1: **procedure** MAPRINGS(N_{RINGS}, N_λ)
2: $\quad AvailableWaveLengths \leftarrow$ Empty
3: $\quad$ **for** $r \leftarrow 1$ to N_{RINGS} **do**
4: $\quad\quad$ DetuneAllRings() ▷ Detune rings, so ring r can see all wavelengths within range.
5: $\quad\quad AvailableWaveLengths \leftarrow$ FindAvailableWavelengths($r, AvailableWaveLengths$)
6: $\quad MatchingWavelengths \leftarrow$ FindMatchingWavelengths($AvailableWaveLengths$) ▷ See Section 3.2
7: $\quad ChannelMap \leftarrow$ MapChannels($AvailableWaveLengths, MatchingWavelengths$) ▷ See Section 3.3
8: $\quad$ **return** $ChannelMap$
9:
10: **procedure** FINDAVAILABLEWAVELENGTHS(r, $AvailableWaveLengths$)
11: $\quad P_{ref} \leftarrow MeasureOpticalPower()$ ▷ Measure reference optical power
12: $\quad V_r \leftarrow 0V$ ▷ Set ring r to 0V
13: $\quad$ **while** $V_r < MAXIMUM(V_r)$ **do** ▷ Do not exceed maximum voltage allowed for the ring
14: $\quad\quad$ **if** LOCALMINIMUM($MeasureOpticalPower()$) **then** ▷ Check if optical power is at local minimum
15: $\quad\quad\quad P_{diff} \leftarrow |P_{ref} - MeasureOpticalPower()|$
16: $\quad\quad\quad AvailableWaveLengths$.ADD($V_{r,i}, P_{diff}$) ▷ Found a wavelength, save it to the list
17: $\quad\quad\quad i \leftarrow i + 1$
18: $\quad\quad V_r \leftarrow V_r + \Delta V$

that wavelength out of the bus waveguide. To measure this, one ring is first tuned to a wavelength of interest and the received optical power P_1 is measured. Then, the another ring is tuned to a previously found wavelength and the received optical power P_2 is measured again. If the difference $|P_1 - P_2|$ is much smaller than the previously measured change in power P_{diff} (Algorithm 1, line 15) it means that both rings are tuned to the same wavelength. The threshold for deciding if if two rings are tuned to the same value depends on the designed bandwidth and quality factor of the rings, as well as the spacing of the wavelengths. Narrow bandwidth, higher quality factor, and wider spacing all increase the difference in optical power between two rings tuned to the exact same wavelength and being tuned to adjacent wavelengths. In our system, the change in optical power is measured by the monitor photo-diode. In a system where each ring is monitored individually, this difference can be measured on the second of the two rings.

This process to is used by the algorithm in Fig. 2 to determine at which voltages each of the micro-rings couple to the same wavelengths. To illustrate the results of this algorithm, an example of what a 4-ring system with 4 wavelengths might measure is shown in Table. 1. First, all rings are detuned to ensure that they do not interfere with the measurements. Next, the algorithm starts with the two highest indexed rings and tries to find at which of the previously found voltages they map to the same wavelength. If no such wavelength can be found, the device is faulty, as it was designed to be able to have rings tune to multiple wavelengths. Once a single matching voltage has been found, all other matching voltages between those rings are known as well, as they are in the same order. In Table. 1, a found matching voltage is shown using an '=' symbol and other deduced matching voltages are placed in the same row.

When micro-rings can be tuned across their entire free spectral range (FSR), or when a large portion of the spectrum within a FSR is filled with the optical signals, it is possible that a ring can lock to different wavelengths using the two resonances at either side of the used optical spectrum. The algorithm will see this as a 'loop' in the matching wavelengths. This is solved by trying to find a matching wavelength between R_N and R_1. In the example in Table 1, this is shown as $V_{4,3}$ matching with $V_{1,1}$.

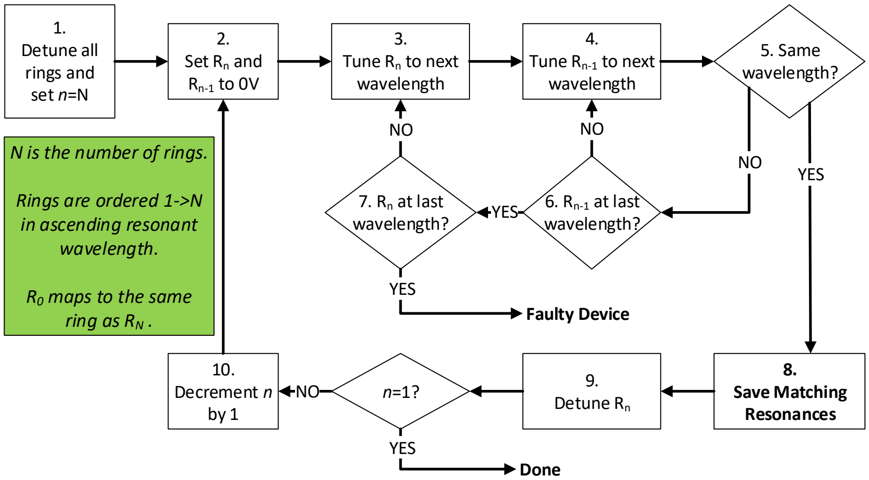


Figure 2: Diagram of FindMatchingWavelengths Algorithm

Table 1: Example result of FindMatchingWavelengths() in a 4-ring system. Found matches indicated by '='.

R_4	R_1	R_2	R_3	R_4
$V_{4,3} =$	$V_{1,1}$	$V_{2,4}$	$V_{3,3}$	$V_{4,3}$
$V_{4,4}$	$V_{1,2} =$	$V_{2,1}$	$V_{3,4}$	$V_{4,4}$
$V_{4,1}$	$V_{1,3}$	$V_{2,2} =$	$V_{3,1} =$	$V_{4,1}$
$V_{4,2}$	$V_{1,4}$	$V_{2,3}$	$V_{3,2}$	$V_{4,2}$

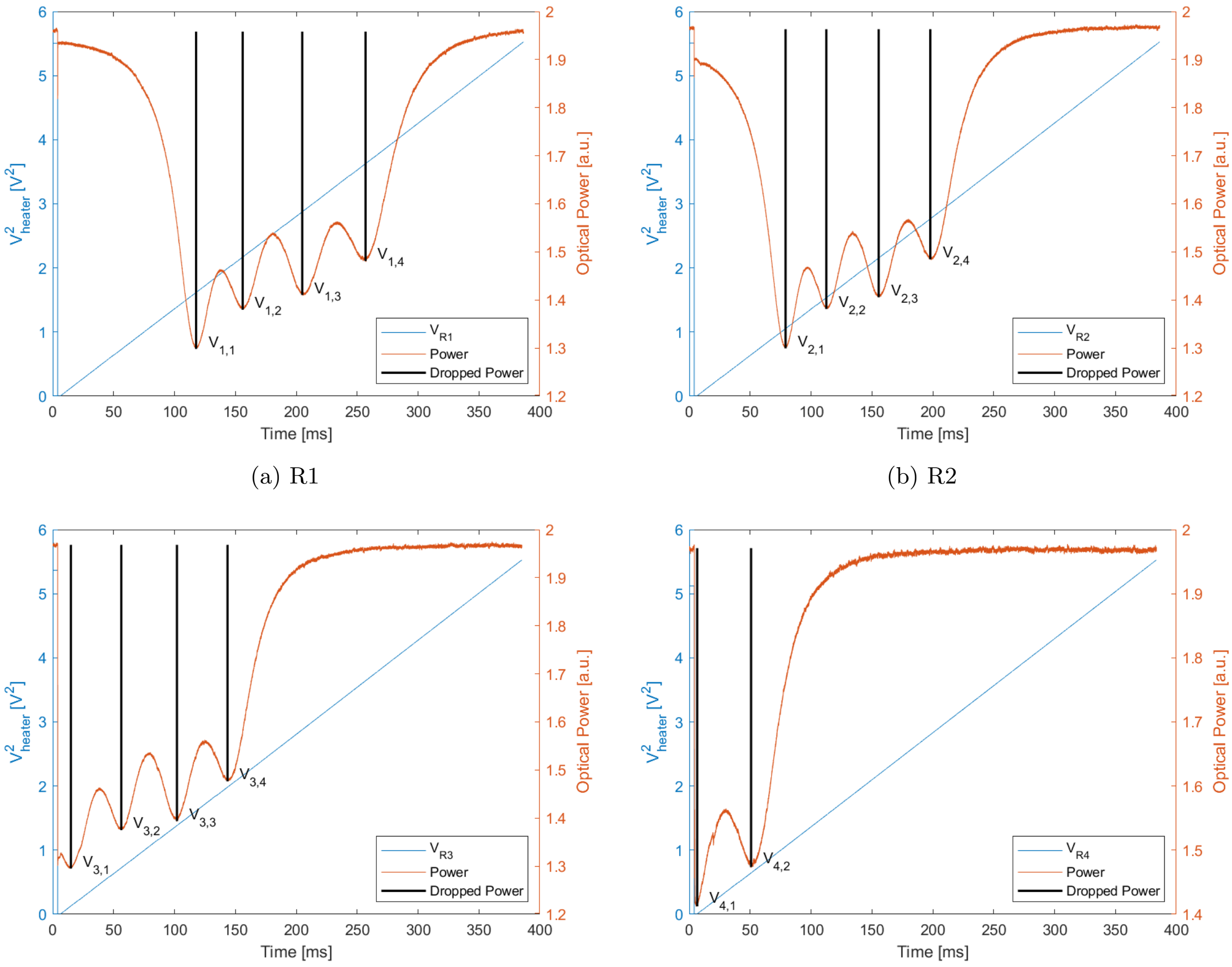
3.3 Mapping Matched Wavelengths to Channels

Once a mapping has been found of which voltages correspond to the same wavelength, the system does not yet know exactly which optical channel they map to. To determine this, some more knowledge of the system's design is required. This is easiest in a system that is designed to not have a loop. $V_{1,1}$ would map to the smallest possible wavelength and channel. Starting from there, the process to map the other channels is straightforward. The difficulty arises is when there is a loop in the matching wavelengths. In such cases, the system must be able to distinguish between a ring moving to the next wavelength, and a ring moving from the largest wavelength using one resonance to the smallest wavelength using another resonance. In a system where the FSR is maximally filled using equally spaced optical channels, it not possible to distinguish these two cases using only simple optical power measurement techniques. For example, in a system that uses 4 optical channels separated by 5nm and micro-rings that have an FSR of 20nm, tuning from the last wavelength to the first wavelength takes the same 5nm of tuning that it takes to tune from one channel to another. Herein also lies the key solving the loop. A system must be designed so that the FSR is greater than the number of channels multiplied by the channel spacing, and wavelengths need to be placed such that requires a ring to be tuned across a greater distance to move from the last to the first wavelength, then it does to tune between adjacent channels. Then, the extra power required to tune from the largest to the smallest wavelength will be more than when tuning from one wavelength to the next wavelength. How much larger the FSR needs to be depends on the fabrication variation, the quality of the measurements, and the resolution of the heater voltage, as the measured difference in power needs to be big enough to be reliably distinguished.

4. RESULTS

4.1 Search for available wavelengths

During the first part of Algorithm 1, the controller searches for the voltages that maximize the received power, which means the rings are detuned as much as possible. Then the algorithm searches for wavelengths that are available to each ring. It does so by first detuning all rings and then scanning through each ring to find at which voltages it is locked to a wavelength, and by how much the received power drops at that wavelength. Fig. 3 shows traces of this process for each individual ring. To speed up the process, the heater voltage is raised such that the square of the heater voltage increases at a constant rate. This works because the power dissipated in each heater is proportional to the heater voltage squared, and therefore the ring's resonances do not shift much for small voltages. All wavelengths that each ring can lock are marked with a black line, of which the height is equal to the measured change in optical power P_{diff}. Because of the close spacing of the wavelengths and bandwidth of the micro-rings the received power does rise to its completely detuned value in between two wavelengths. From



(a) R1

(b) R2

(c) R3

(d) R4

Figure 3: Trace of search for available wavelengths. Heater voltage squared (blue) and received optical power (red) vs. time. The black lines indicate each found wavelength and the measured drop in optical power when the ring is locked. While each ring is searched, other rings are detuned.

this figure we can also see that R1, R2, and R3 can tune to all four optical channels, but R4 can only tune to two optical channels.

4.2 Matching wavelengths

After searching for all available wavelengths, and measuring the change in received optical power, the algorithm will attempt to find which wavelengths of different rings correspond to the same optical signal. To do this the algorithm first tunes a ring to one of its wavelengths and . It then cycles an adjacent ring through its available wavelengths. For every attempted wavelength the difference in power between only until it finds one that causes a much smaller change in optical power than it during the initial search, which means that both rings are tuned to the same wavelength. We see this by comparing Fig. 4 with Fig. 3c. They both show a trace of the wavelength search for R3, but R2 is set to its second wavelength during the trace shown in Fig. 4. R2's wavelength is clearly missing and at the same tuning voltage of R3, the drop in optical power is much smaller. Fig. 4 also shows what the thresholds are the algorithm uses to determine if R3 is tuned to the same wavelength as another ring. This threshold is only met for the wavelength R2 is tuned to. With the device we used, a threshold of half of P_{diff}

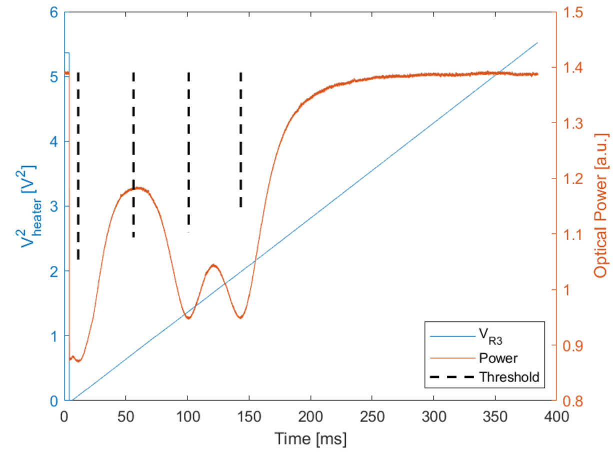


Figure 4: Trace of search for wavelengths for R3, while R2 is set to its second wavelength. Also indicated is the threshold for deciding when R3 is set to the same wavelength as another ring, which is only reached when matching with R2.

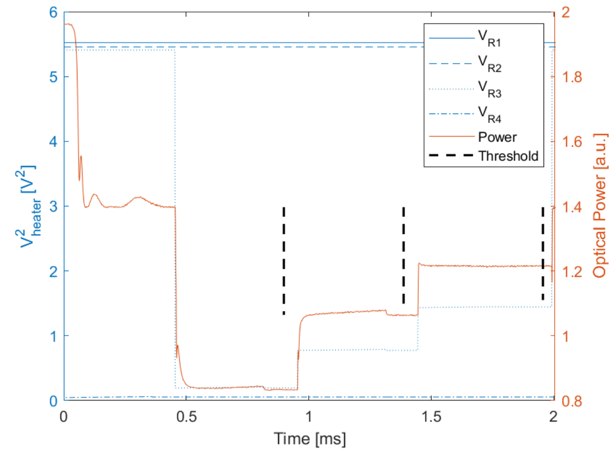


Figure 5: Trace of search for for matching wavelength between R3 and R4. R1 and R2 are set to their detuning voltages. Also indicated are the decision thresholds for each of the attempted wavelengths R3 is set to.

resulted in reliable determination of matching wavelengths. Fig. 5 shows a trace of this matching process when matching R3 and R4. First R4 is set so its first available wavelength. Then R3 is stepped through its available wavelengths until the third wavelength meets the threshold. For rings R1 through R3 the algorithm correctly determines that the first wavelength of those rings matches with each other.

4.3 Combining measurements with design parameters

Because the rings in our device were not tuned an entire FSR it is straightforward to determine to which channel each of the rings's wavelengths map. From the design of the system the algorithm knows that there are four optical channels, and rings R1-R3 are all able to tune to four wavelengths. Therefore the first wavelength of each rings maps to the lowest wavelength channel (ITU channel 60). And the other wavelengths then map to the subsequently higher wavelength channels, channels 59, 58, and finally 57. The algorithm determined that R4's first wavelength is the same as R3's third, which is ITU channel 58.

4.4 Determining a switch in resonance

Because our device cannot tune the entire FSR, we cannot show how the algorithm can determine when a ring switches from the highest wavelength using one resonance, to the lowest wavelength using the previous resonance. However, since this is done by comparing the increase in power that is required to shift from one wavelength to the other, we show that the algorithm can measure the larger shift when two wavelengths are spaced further apart. To do this, we launched ITU channels 57 through 60, each spaced 0.8nm, and channel 55, which has 1.6nm spacing from channel 57. The controller then searched for available wavelengths. Fig. 6 shows the square of the heater voltage required to tune to each ITU channel. The fitted lines shows that the increase in power to tune between channels 57 through 60 is almost constant, while the change from 57 to 55 is significantly more. By designing designing a system such that it takes a larger shift to go from the last wavelength to the first, a similar change in required power will be measured, and this can be used to determine which of the found wavelengths are the first and last channels.

5. CONCLUSIONS

The capability to tune cascaded micro-ring resonators exactly the right channel is required in many types of systems, and can also be useful in systems where this is not a requirement. In this last case, there might be

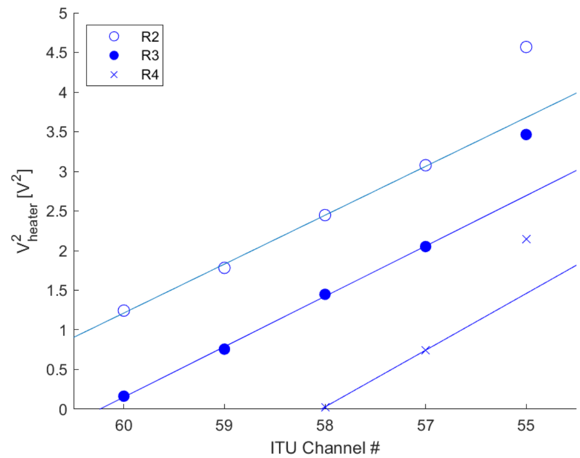


Figure 6: Square of heater voltage required to tune rings R2, R3, and R4 to each of the launched ITU channels. The fitted lines show that it takes significantly more power to shift from channel 57 to 55 then between the other channels.

multiple possible configurations of the rings, and by know exactly to which channel they are tuned, one can choose the configuration that uses the smallest amount of power for the ring tuning. In this work we have proposed an algorithm to tune cascaded micro-ring resonators to exactly their desired optical channels using only simple techniques to measure optical power and knowledge of the system's design. We have experimentally shown that this algorithm works for a system where the rings cannot fully tune an entire FSR. For the case where rings can tune an entire FSR, they the FSR must be larger than the number of channels multiplied by the channel spacing. We have also shown, that in that case, we can measure the extra shift required for a ring to tune from the last wavelength to the first. This is done using only simple optical power measurements and knowledge of the system's design. Using this technique, it is not necessary to measure the wavelength of light being coupled into the micro-rings, or extensively characterize each ring for fabrication variations and ambient temperature.

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