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Microwave power induced resonance shifting of silicon ring modulators for continuously tunable, bandwidth scaled frequency combs

K. P. NAGARJUN,[1,2,3] PIYUSH RAJ,[1,2] VADIVUKKARASI JEYASELVAN,[1] SHANKAR KUMAR SELVARAJA,[1] AND V. R. SUPRADEEPA[1,4]

[1] *Centre for Nano Science and Engineering, Indian Institute of Science, Bengaluru 560012, India*
[2] *These authors contributed equally to this paper*
[3] *nagarjunkp@iisc.ac.in*
[4] *supradeepa@iisc.ac.in*

Abstract: We demonstrate a technique to continuously tune center frequency and repetition rate of optical frequency combs generated in silicon microring modulators and bandwidth scale them. We utilize a drive frequency dependent, microwave power induced shifting of the microring modulator resonance. In this work, we demonstrate center frequency tunability of frequency combs generated in silicon microring modulators over a wide range (~8nm) with fixed number of lines. We also demonstrate continuously tunable repetition rates from 7.5GHz to 15GHz. Further, we use this effect to demonstrate a proof-of-principle experiment to bandwidth scale an 8-line (20dB band) comb generated from a single ring modulator driven at 10GHz to a comb with 12 and 15 lines by cascading two and three ring modulators, respectively. This is accomplished by merging widely spaced ring modulator resonances to a common location, thus coupling light simultaneously into multiple cascaded ring modulators.

1. Introduction

Optical frequency combs consist of uniformly spaced, coherent lines in wavelength space that have found extensive applications in areas of spectroscopy [1,2], sensing [3,4], distance ranging [5,6] etc. In the C-band, frequency combs have been considered for their use in microwave photonics [7,8] as well as wavelength division multiplexing (WDM) sources for transmitters in high-bandwidth optical communications [9,10].

On-chip optical frequency comb generation has recently been investigated in CMOS compatible material platforms like silicon nitride [10,11], silicon oxide [12], hydex [13] aluminum nitride [14] etc. that typically use cascaded four-wave mixing and soliton processes in wavelength stabilized, microring resonator structures resulting in large bandwidth combs but with fixed repetition rate and limited center frequency tuneability. For optical communication applications, it is desirable that frequency combs have tunable center frequency and flexible channel spacing.

In our previous work [15,16] we proposed and experimentally realized on-chip frequency comb generation using large signal modulation of an optical carrier in linear charge injection based silicon modulators. Frequency combs generated in such devices are attractive since they are easily integrated with pre-existing silicon photonics components without additional coupling losses, have continuously tunable center frequency and repetition rate and are CMOS fabrication compatible etc. Combs generated in linear modulators have since been used in different configurations and applications for e.g. in Mach-Zehnder modulators(MZM) [17], cascaded MZM with phase modulators [8], dual-drive MZM [18], dual-parallel MZM configurations [19] etc.

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Alternately, a more compact implementation can be realized using silicon based PN doped microring modulators [20–22]. Microring modulators are commonly used in on-chip silicon transceiver systems for wavelength selective data modulation and demodulation operations. Here, comb lines are generated only when an input optical carrier is located at a microring modulator resonance. This, however, constrains the continuous center frequency and repetition rate tuning of the ring modulator-based comb generator. Using additional external mechanisms such as an on-chip heater, limited tuning in center frequency can be achieved. In this work, we demonstrate simple mechanisms to overcome this constraint without the need of external compensation mechanisms.

In both linear and microring modulator systems, the number of comblines generated can be increased by varying device properties like doping concentration, or by increasing drive RF-power which requires cost ineffective use of higher power RF-amplifiers apart from requiring the addressing of critical modulator power handling issues [23]. Another technique is to input multiple optical carriers offset from each other into a single modulator and phase lock their resultant frequency combs [24]. However, this technique requires the additional setup of optical phase locked loops to frequency lock the output combs to form a single composite frequency comb. Additionally, this technique is unsuitable for bandwidth scaling microring modulator based comb generators; since input carriers would have to be located only at ring modulator resonances.

Alternatively, a simple technique to increase frequency comb lines in linear modulator based comb generators is to increase the modulator half-wavelength as seen by the optical carrier. This can be accomplished by cascading multiple modulators driven from a common RF-source with phase shifters to appropriately align the temporal phases of the modulators [25,26]. However, cascading of multiple ring modulators requires the precise positioning of independent ring modulator resonances to a common location in order to simultaneously couple light to all modulators. This would necessitate very tight fabrication tolerances or again would need additional compensation such as using on-chip heaters. In this work, we overcome this constraint as well by demonstrating a novel approach to achieve bandwidth scaling of optical frequency combs generated in microring modulators by cascading multiple microring modulators to a common bus waveguide.

We achieve both continuous center frequency and repetition rate tuning as well as bandwidth scaling by exploiting the effect of large-signal microwave power on silicon ring-modulator cavity resonances. We first demonstrate that large signal microwave power typically used for frequency comb generation, induces tunable thermo-optic redshifts of several nanometers of the cavity resonance accompanied by a degradation of the Q-factor and extinction. We also demonstrate the effect of drive frequency on this microwave power induced thermo-optic shift. Far from being an unwanted effect, we show that this phenomenon enables us to (i) achieve a wide range of tuneability of center frequency at different repetition rates of the frequency comb, and (ii) achieve scalable comb broadening in ring modulator-based comb generators by cascading them. We show a proof of concept demonstration where we achieve center frequency tuneability over several nm and continuously tunable channel spacing from 7.5GHz to 15GHz without any degradation in the number of comb lines. We also show bandwidth scaling starting with 8 lines at 10GHz channel spacing, generated using a single modulator in a 20dB power band scaled to 12 lines using two cascaded modulators and 15 lines using three cascaded ring modulators.

Furthermore, we note that, to the best of the authors' knowledge, continuous center frequency, repetition rate tuneability and cascading of ring modulators to achieve bandwidth scaling has not been demonstrated in silicon microring modulator based frequency combs so far. Finally, we note that the microwave power induced thermo-optic shifting of the resonance described in this paper can be used to compensate for process variations in microring-modulator fabrication.

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2. Experimental results

A silicon based microring PN doped modulator with a radius of 7.6um and Free Spectral Range (FSR) of 13nm is fabricated on a 220nm Silicon-on-insulator (SOI) wafer through a Europractice multi-process wafer (MPW) run [27]. The bus waveguide is a 180nm from the ring. Light is fiber coupled into and out of the bus-waveguide using on-chip grating couplers. The grating coupler loss is ~3.5 dB per coupler with a passive waveguide loss of ~2dB/cm at 1550nm. We first investigate the effect of high-frequency, large signal microwave power on the optical response of the ring modulator at zero DC-bias. For this task [28], we chose a low power broadband (SLED) superluminescent diode as the input with a power of -0.3dBm spread over 45nm (from 1530nm to 1575nm) (Fig. 1(a)). We chose this low power broadband source in order to avoid any significant free carrier absorption (FCA) or two-photon absorption (TPA) effects from affecting the cavity resonance spectra. RF-power and DC-bias signals are coupled into the ring modulator through a bias-tee, using high-frequency Ground-Signal configuration RF-probes. A sinusoidal signal at fixed frequency of 10 GHz is swept from 10 mW to 320 mW source power using a microwave signal generator having a 50 ohm output impedance (Fig. 1(a)). The device is typically used for high-speed electro-optic data modulation operations utilizes lumped electrodes without any matching network. We acquire optical spectra (Fig. 1(b)) of the ring-resonance which is initially at 1547.56nm that redshifts by 7.9 nm (Fig. 1(c)) when driven by a source power of 320mW to 1555.52nm. This large red-shifting of the ring modulator resonance is also accompanied by a deterioration of the ring extinction ratio as well as Q-factor by a factor of three (Fig. 1(d)).

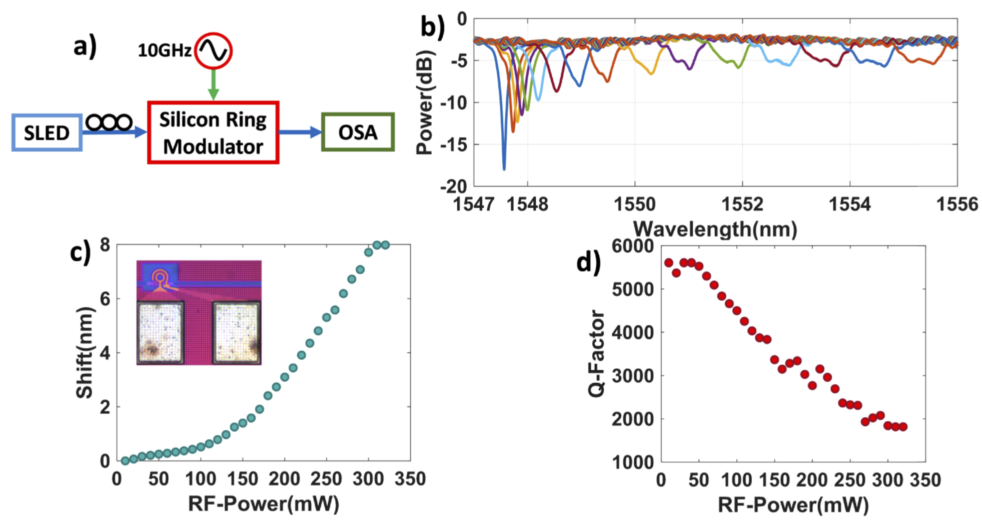

Fig. 1. a) A wide span superluminescent diode (SLED) at low power is used to characterize the effect of microwave power on a silicon microring modulator (OSA: optical spectrum analyzer). (b) Transmission spectra showing the effect of microwave power swept from 10 mW to 320 mW, in steps of 20 mW on the ring modulator resonance (c) The ring-modulator resonance undergoes a microwave power induced thermo-optic shift of ~8 nm at 320 mW of source power (from 1547.56 nm to 1555.52 nm), inset: microscope image of the silicon microring modulator (d) deterioration in Q-factor by a factor of ~3.

The degradation of the ring modulator resonance can be attributed to field-induced free carriers in the ring cavity waveguide that remain at large microwave powers and frequency, that cause the microring modulator to have higher absorption in comparison to no applied microwave power. We note that, while the ring modulator resonance instantaneously responds to the applied time-varying bias, the observed resonance shift of the ring modulator is due to thermo-refractive

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changes induced at the ring due to localized device power dissipation from these carriers. The red-shifting of the modulator resonance location is fundamentally the result of a slower thermal process. The measured location of the degraded modulator resonance reflects this shift as seen by the optical spectrum analyzer.

When the microring modulator bias is swept from -6 V to +1.4 V with no applied microwave power, the resonance exhibits well-known blue-shifting of ~4.7 nm which is accompanied with much higher free carrier absorption that completely extinguishes the resonance at ~1.4 V.

In contrast, when the device is purely driven by microwave power, the time-varying opposing voltage swings limits the FCA due to carriers being partially swept out of the junction, while allowing for the dominating thermo-refractive effect to red-shift the ring modulator resonance to large values.

We also find this effect to be dependent on drive frequency. The microring modulator resonance undergoes larger resonance shifts at lower drive frequency (Fig. 2) for e.g. at 5GHz drive frequency, the ring modulator resonance red-shifts by ~10.5nm when driven by 250mW of source power.

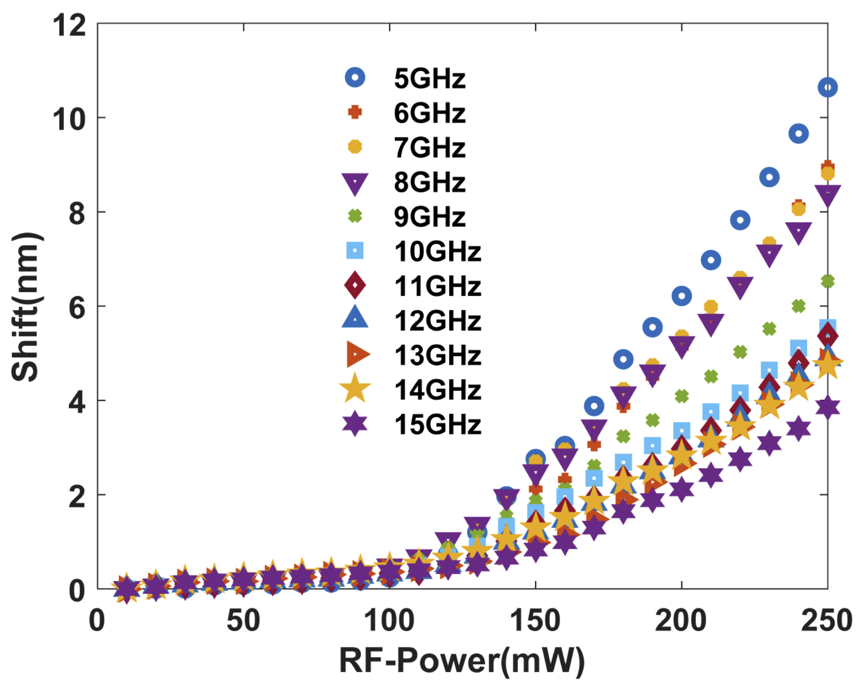

Fig. 2. Drive frequency dependence of ring resonance shift at different drive microwave powers from 5 GHz to 15 GHz.

In this work, microwave power based tuneability of the microring modulator resonance is used to a) demonstrate center frequency and repetition rate tuneability of optical frequency combs generated using strong carrier modulation in silicon ring modulators and b) demonstrate a technique to bandwidth scale frequency combs generated in these ring modulators by cascading multiple modulators to a common bus waveguide.

2.1. Application-1: repetition-rate and center frequency tuneability

An independently tunable repetition rate and center frequency is desirable in optical frequency combs used for various applications like optical arbitrary waveform generation, microwave photonics and optical communications [17,25]. In the Electro-Optic (EO) comb generation method, large-signal microwave power is typically used to strongly modulate an optical carrier to generate multiple carriers that constitute the frequency comb lines. The thermo-optic shifting of the resonance arising from this drive power is thus forced upon this system. In this section, we demonstrate how this microwave power induced thermo-optic effect can be exploited to generate combs with these properties.

We start by using microwave power from a signal generator to customize the location of the degraded microring modulator resonance in order to tune the center frequency. Broader and flatter frequency combs are generated, when the associated ring modulator resonance is both wide and has a moderate extinction. This condition allows for maximum generated comb lines to successfully out-couple to the bus waveguide. We then generate frequency combs by coarsely positioning a Distributed Feedback (DFB) laser with +5.5dBm source power approximately at the center of the degraded ring modulator resonance (Fig. 1(b)).

The frequency comb center frequency and repetition rate can be continuously tuned without degradation in the number of lines over a wide range of values, as demonstrated in (Figs. 3(a)-(d)) where repetition rate, is varied from 7.5GHz to 15GHz.

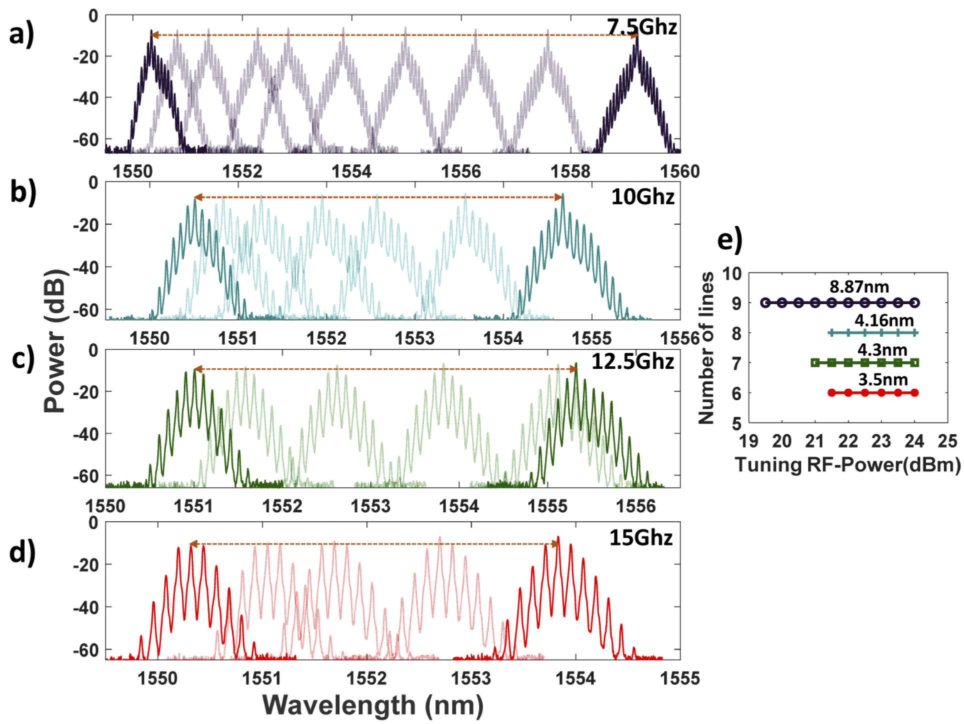

Fig. 3. Microwave power induced thermo-optic tuning of ring modulator resonances allows for wide center frequency tuneability of several nm. Here shown with combs driven at different repetition rates (a) 7.5GHz (9 lines) (b) 10GHz (8 lines) (c) 12.5GHz (7 lines) and (d) 15GHz (6 lines). (e) The tuning range of the center frequency for the repetition rates used in (a) to (d) as a function of applied microwave power. Data is acquired in steps of 0.5dB and in each case, the comb maintains the same number of lines.

We also tune the frequency comb center frequency by varying microwave power and thus relocating the microring modulator resonance to different optical carrier locations as described in the previous section. Figure 3(e) shows a fixed number of comb lines in a 20dB band that can be maintained over a microwave power tuning range, for each repetition rate. Representative plots of the spectra are obtained (Figs. 3(a)-(d)) while microwave power is varied at steps of 0.5dB.

For example, 8 lines can be maintained across a center frequency tuning range of 4.16nm at a comb channel spacing of 10GHz by tuning RF power by 21.5dBm to 24dBm. Below the lower end of this tuning range, the number of comb lines that can be maintained decreases. We note that the total microwave power variation in this regime is around 4 dB for the 7.5 GHz case and less than 3 dB for the 10 GHz and above repetition rates. This change does not significantly alter the comb profile and retains the number of lines in this margin.

While the range of center frequency tuning reduces for narrower power margins, we note that the observed comb spectral envelopes and flatness in this demonstration are specific to our generic foundry fabricated devices. The modulators if required can be further optimized to generate flatter and broader comb profiles for applications requiring narrower margins for e.g. by tuning the loss modulation effects at the device level etc. We also note that the proposed technique is feasible and independent of the choice of the flatness margin used here which can be chosen based on application of interest.

We can additionally tune DC-bias (around 0V) applied to the ring modulator via a bias-tee, which displaces the location of the modulator resonance relative to the position of the input optical carrier. This allows for tuning of the generated frequency comb envelope, flatness as well as number of comb lines [20]. We manually tune the center wavelength of the DFB and the DC bias to maximize the flatness of the comb profile and the number of comb lines. We will later describe a more general feedback-based optimization technique that can be used to continuously monitor changes in the center frequency location and maximize the number of generated comb lines for that location, for ring modulator banks with multiple modulators. For the single modulator system we manually tune the bias and laser position to generate 8 lines in a 20dB band using 10GHz channel spacing (Fig. 3(b)), comparable to other silicon microring modulator frequency comb generators in literature [20,22].

The microwave power only drive system proposed here has the added advantage of self-adjustment, i.e. even if the exact ring modulator resonance is not known or not matched to the drive laser wavelength location, the microwave power when varied, will allow for the induced resonance shift to match the laser wavelength and induce comb generation. This results in a high degree of operational flexibility which avoids two independent control parameters i.e. one for the thermo-optic heater and another for the DC-bias, each of which require independent close loop operation.

2.2. Application-2: bandwidth scaling through cascading ring modulators

A ring modulator bank consists of multiple ring modulators of varying size having discretely spaced neighbouring cavity resonances and is typically used to modulate wavelength multiplexed data to a common bus waveguide for short-haul WDM applications [29]. However, cascading of such ring modulators having discretely spaced resonances for frequency comb bandwidth scaling requires the precise alignment of multiple microring resonances to a common location in order to collectively utilize the multiple ring modulators simultaneously (Fig. 4(a)). This requirement adds tight fabrication process variation constraints on the ring dimensions or require external compensation for e.g. through on-chip heaters. In this section, we demonstrate that microwave power induced thermo-optic shifts can be used to circumvent this limitation and enable bandwidth scaling of combs by cascading of ring modulators.

We consider a microring modulator transmitter bank consisting of four ring modulators with different radii (7.68um, 7.59um, 7.5um and 7.41um) all coupled to a common bus waveguide spaced 180nm from the rings to accomplish bandwidth scaling of on-chip combs used in setup (Fig. 4(b)). The rings don't optically couple to each other. The resultant individual resonances of each ring are initially located at (1546.91nm, 1547.92nm, 1549.86nm and 1550.61nm) (Fig. 5(a)). We drive the latter two modulators that have a radial dimension difference of ~100nm with microwave power and shift their resonances which are initially located at 1549.86nm and

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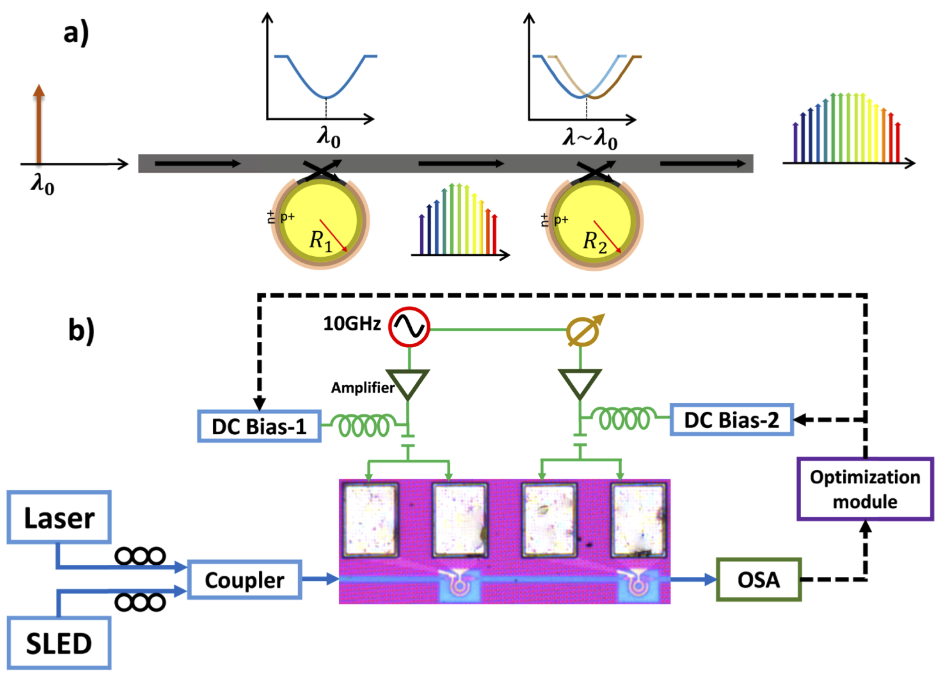

Fig. 4. (a) Technique to bandwidth scale frequency combs generated through cascading of silicon microring modulators. Here a laser at λ_0 is coupled simultaneously to two ring modulators that are optically coupled to a common bus waveguide. The microring modulators are driven with microwave power to align and tune their respective resonances to a common location λ using microwave power induced thermo-optic shift. (b) Setup used for bandwidth scaled frequency comb generation by cascading two ring modulators. Two microring modulators with radius of 7.68um and 7.59um have initial resonance locations at 1549.86 nm and 1550.61 nm respectively. The SLED source is used to trace the movement of the ring modulator resonances.

1550.61nm and merge them at a common location of 1554.72nm (Figs. 5(b) and (c)). This is accomplished by driving them with slightly different microwave powers.

We further augment this setup with a feedback based DC-bias tuning scheme to maximize the number of comb lines generated. We implement a computer-based Bayesian optimization with DC-bias as the tuning parameter (Fig. 4(b)). In this scheme, when the center frequency is tuned to a new location, a SLED source which is co-coupled into the rings is used to track the location of the merged ring resonance on an OSA. The DFB laser is then coarsely positioned to this new merged resonance location. We then fine tune the individual DC-biases by using a multivariable Bayesian optimization technique. The DC-biases of both rings are iteratively varied to maximize the number of comb lines generated, given the approximate location of the optical carriers and the merged resonance.

Using this scheme, we can generate 12 lines in a 20dB band (Fig. 5(d)) using an input optical carrier with power of +5.5dBm. This input carrier is now simultaneously optically coupled to both modulators, which have a common merged resonance location and the ring modulators are effectively cascaded. The combined system now generates an increased number of comb lines compared to a single modulator system (Fig. 3(b)). We can further extend this technique by cascading a third microring modulator with radius 7.59um of the same transmitter bank and merge their individual resonances at 1549.05nm resulting in 15 lines in a 20dB band having a channel spacing of 10GHz (Fig. 5(e)).

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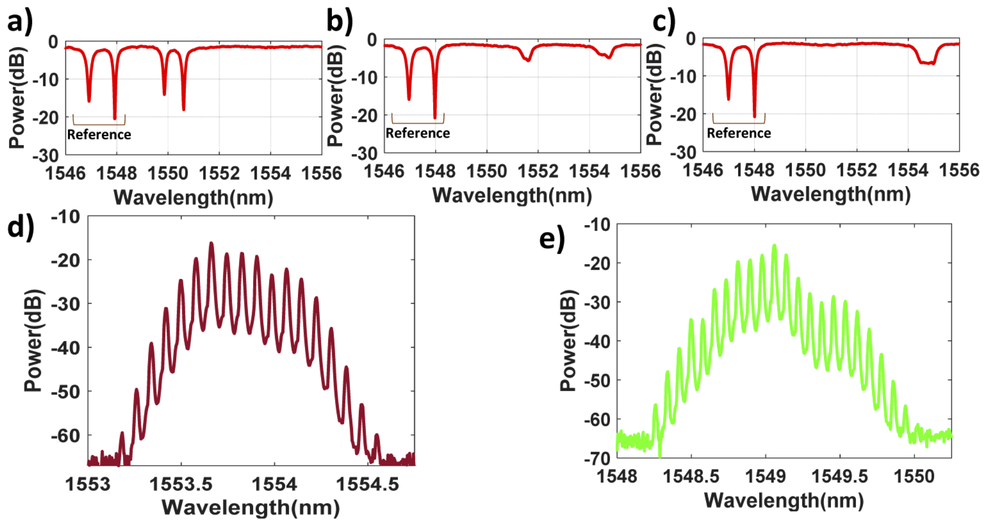

Fig. 5. a) Cascaded Ring modulator bank resonances with (no RF-power) containing 4 rings with resonance locations at 1546.91 nm, 1547.92 nm, 1549.86 nm, 1550.61 nm coupled to a common bus waveguide b) RF-power at 10 GHz applied to two ring modulator resonances leading to microwave power induced thermo-optic shifts. c) The RF-power applied to the ring modulators is tuned to merge the resonances to a common location (~1554.72 nm). d) Optimized 10 GHz repetition rate combs generated from cascading two ring modulators with 12 lines in a 20 dB band with a center frequency of 1553.82 nm. e) Cascading three ring modulators using a different set of merged resonances resulting in 15 lines in a 20 dB band with a center wavelength of 1549.05 nm.

We observe that the number of comb lines does not scale in proportion to the number of modulators as in bulk pure phase modulation based electro-optic comb generators [25]. This is due to the presence of additional amplitude modulation in the integrated charge injection-based modulators. Amplitude modulation results in shorter temporal features which results in reduced sampling of the phase modulation imparted and thus, progressively reduces the impact of additional modulators [26]. There has been recent work [30] which enables integrated silicon modulators that achieve pure phase modulation without the accompanying amplitude modulation. Using such modulators, favorable bandwidth scaling can be achieved with cascading of more modulators.

It is possible to retain tuneability of center frequency in combs generated from a cascaded system of ring modulators (Fig. 6). With frequency combs generated from a cascade of two ring modulators, 11 lines in 20dB power band is maintained over a center wavelength tuning range of ~2nm from 1552.58nm to 1554.76nm. This is easily accomplished by tuning both RF-amplifier gains (Fig. 4(b)) thus allowing for the merged resonance to be relocated as required. With the Bayesian optimization constantly tuning the DC-bias, the bandwidth scaled combs were found to be stable for over 9 hours of continuous operation.

Importantly, we note that bandwidth scaling and continuous tuneability of center frequency and repetition rate is accomplished in our approach without use of additional thermo-optic heaters. This also allows for eliminating an additional element for independent feedback stabilization as well as extra fabrication steps required for these thermo-optic heaters.

While bandwidth scaling of comb lines using multiple nearly identical cascaded ring modulators has been attempted in [21], the proposed technique makes use of thermo-optic heaters additionally to compensate for fabrication variations of the individual ring modulators and tune the locations

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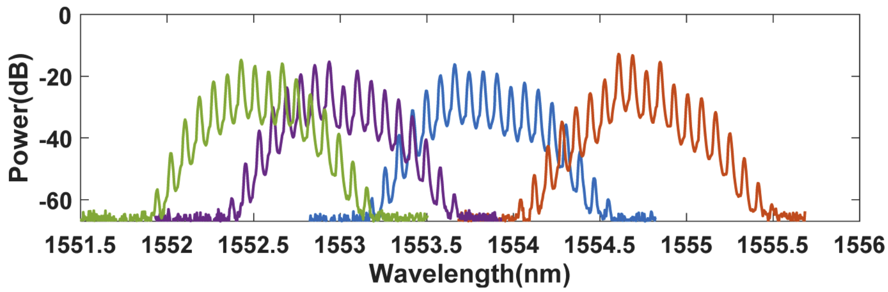

Fig. 6. Centre frequency tuning of ~2 nm (from 1552.58 to 1554.76 nm) in 10 GHz repetition rate optical frequency comb with 11 lines in a 20 dB band, generated by cascading two on-chip silicon microring modulators.

of the interleaving harmonics generated in order to align to neighboring resonances of other ring modulators, which then generate harmonics of their own to form a multiwavelength source. Such an approach to bandwidth scaling requires heater feedback stabilization as well as the use of phase referenced two-tone drive, in multiples of the desired comb repetition rate in contrast to the technique described in this paper.

3. Summary and future work

In this work, we reported the effect of large signal microwave power on silicon ring modulator resonance. Large signal microwave power induces a drive frequency dependent thermo-optic shift and degrades the Q-factor of the ring modulator resonance. The proposed techniques are independent of the specific implementation and were used to demonstrate a) center frequency tuneability of several nm of optical frequency combs generated using ring modulators at different repetition rates and b) a preliminary demonstration of bandwidth scaling of ring modulator combs from 8 lines in 20 dB with a single modulator to 12 and 15 lines by merging resonances and hence cascading two and three ring modulators respectively. A robust bandwidth scaled comb can thus be generated on-chip in silicon by coupling a single optical carrier to multiple ring modulators in a cascaded configuration. The number of generated comb lines as well as device power consumption can also be improvised through use of appropriate impedance matching networks. Finally, we note that the techniques proposed here are not limited only to silicon platform but may also be engineered for all other charge injection based photonic material systems.

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Disclosures

The authors declare no conflicts of interest.

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