Energy-Efficient Channel Alignment of DWDM Silicon Photonic Transceivers

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***Abstract*—The comb laser-driven microring-based dense wavelength division multiplexing silicon photonics is a promising candidate for next-generation optical interconnects. However, existing solutions for exploring the power-performance trade-off of such systems have been restricted to a limited design space, resulting from the unnecessary constraints of using an identical spacing for laser comb lines and microring channels, and of utilizing consecutive laser comb lines for data transmission. We propose an energy-efficient channel alignment scheme that aligns the microring channels to a subset of laser comb lines that are non-uniformly distributed in the free spectrum range of the microrings. Based on a well-established process variation model, our simulations show that the proposed scheme significantly reduces the microring tuning power in the presence of denser comb lines. The power saved from microring tuning can improve the overall system energy efficiency despite some power wasted in unused laser comb lines. We further conducted a case study for design space exploration using the proposed channel alignment scheme, seeking the most energy-efficient configuration in order to achieve a target aggregated data rate.**

I. Introduction

Dense wavelength division multiplexing (DWDM) silicon photonics has been proposed as a cost-effective solution to the next generation of high-throughput, energy-efficient optical interconnects [1], [2]. A promising approach to multi-channel DWDM prefers a multi-wavelength quantum-dot (QD) comb laser [3] to an array of single-wavelength lasers [4] due to the ease of temperature control, wavelength tracking and packaging of the former [5]–[7]. Cascaded microring modulators and filters are suitable candidates for short-reach DWDM solutions because of their compact footprint, low power consumption and (de)multiplexer-free architecture [8]–[10].

In microring-based optical links, the microring radii are designed to provide a set of discrete resonance wavelengths with a constant channel spacing [5]–[10]. Due to process variations, the resonance wavelengths of the fabricated microrings are not exact, and require extensive tuning to align with the carrier wavelengths [11]. The microring tuning power has been identified as one of the greatest contributors towards the system power consumption [12], [13]. Techniques such as channel remapping, redundant microrings and transceiver optimal pairing [14]–[16] are proposed to reduce the average tuning power. However, assumptions made in these studies are over-simplified. Besides, all of the mentioned techniques unnecessarily assume an identical spacing for laser comb lines and microring channels, resulting from a naïve channel alignment scheme where consecutive comb lines are used for data transmission (hereinafter the *consecutive channel alignment scheme*). Under this scheme, it seems intuitive that to utilize a comb laser with the same spacing as the microrings would statistically lead to the minimum expected tuning power [11]. As a result, the laser comb spacing is often left out of the design space of DWDM silicon photonics [17], [18].

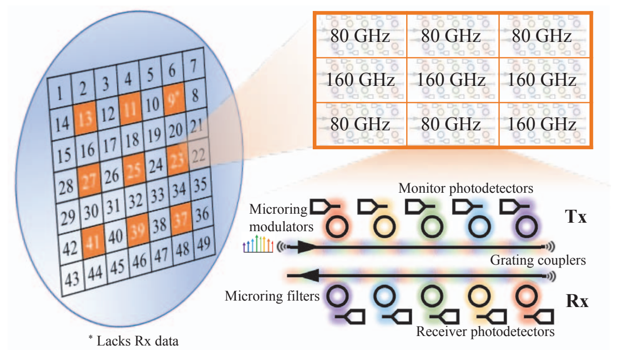

Fig. 1. An illustration of the fabricated transceivers from which the process variation model for resonance wavelengths is extracted.

However, our simulations show that in the presence of denser comb lines, a more flexible channel alignment scheme may further reduce the power consumption of microring tuning. The proposed scheme aligns the microring channels to a subset of laser comb lines that are non-uniformly distributed in the free spectrum range (FSR) of the microrings (hereinafter the *non-uniform channel alignment scheme*). The simulations reveal that despite some power wasted in unused laser comb lines, the overall system energy efficiency can benefit from the reduction of the microring tuning power. Our scheme therefore incorporates the laser comb spacing as another design parameter to be explored.

II. Multi-Channel Microring Transceiver

1) Overview: We extracted the resonance wavelengths of a batch of fabricated transceivers from measurement data. The fabricated wafer consists of 49 dies, of which nine representative ones (highlighted with red color in Fig. 1) are measured. Each die consists of nine transceivers with either 80 GHz or 160 GHz channel spacing. Each transceiver has five high-speed microring modulators on the Tx side for on-off keying modulation, and five corresponding microring filters on the Rx side for demultiplexing. The microrings are ~10 μm in diameter with an FSR of ~13.9 nm, which can accommodate up to 30 channels at 80 GHz spacing in 1310 nm regimn. An example of the measured optical spectrum of the transceiver is shown in Fig. 2(a).

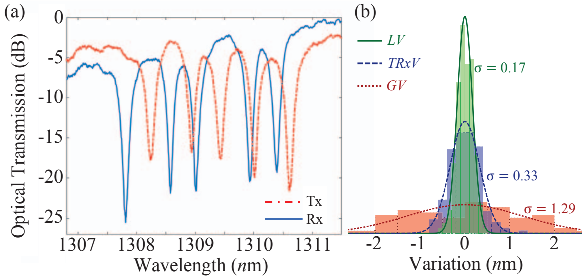

Fig. 2. (a) The measured optical spectrum of a five-channel transceiver with 80 GHz channel spacing. (b) The distribution of the variation components and the fitted Gaussian curves for transceivers with 80 GHz channel spacing.

2) Process variation model for resonance wavelengths: The model featured in this study is modified from the one proposed in [16], where the resonance wavelength of each microring is decomposed into the design value and several variation components. Specifically, the jth channel of the ith transceiver has the resonance wavelength expressed by Eq. (1), where λ_0 is the design value of the first channel, Δf is the channel spacing in frequency domain, and c is the speed of light. The global variation term (GV) and the Tx-Rx offset term $(TRxV)$ are shared by all microrings within one transceiver, while the local variation term (LV) is independent for each microring. Note that in this modified model, the channel spacing is not converted into wavelength domain as in [16], in order to avoid error accumulation when the number of channels is large.

$$\begin{aligned} \lambda_{TX}(i,j) &= \frac{c}{(c/\lambda_0 - (j-1)\Delta f)} + GV_i + LV_j \\ \lambda_{RX}(i,j') &= \underbrace{\frac{c}{(c/\lambda_0 - (j'-1)\Delta f)}}_{\text{Design value}} + \underbrace{GV_i + LV_{j'} + TRxV_i}_{\text{Variation components}} \end{aligned} \tag{1}$$

Based on the extraction results, all of the three variation components are approximated by normal distributions with zero mean, as shown in Fig. 2(b).

3) Power model of the transceiver link: The authors of [17] proposed a model for various power penalties present in a microring-based DWDM optical transceiver. In this study, lookup tables of power penalties are made for different channel spacings, channel counts and per channel data rates, based on the values reported in [17]. The minimum required laser power is obtained by adding up the power penalties of the optical link and the sensitivity of the receiver, which is computed as 1.03 mW per comb line at 10 Gb/s channel rate, and 2.30 mW per comb line at 25 Gb/s channel rate. The results are consistent with both actual measurements [5], [7] and technology projections [3], [19]. The power consumption of the modulator driver and the receiver transimpedance amplifier (TIA) at different data rates are sampled from [18]. The microring tuning power, as one of the optimization targets in this study, is detailed in Section IV.

III. Quantum-Dot Comb Laser

The choice of the laser comb spacing is a result of the optimization of the laser design, especially in terms of wall-plug efficiency (WPE), with which the laser diode converts electrical power into optical power. In practice, a cavity length of 500-1000 μm (40-80 GHz comb spacing) usually leads to the optimum [5]. The comb laser should demonstrate little relative intensity noise (RIN) in 1310 nm or 1550 nm regime [20], which is suitable for fiber optics. In other words, once the QD comb laser is stabilized at its optimal operating point, further tuning of the comb lines is undesirable for avoiding the introduction of excessive noise into the operating band. Therefore, in this study, the laser comb lines are assumed to be fixed at their designed wavelengths, and the microring channels are unilaterally tuned towards the carrier wavelengths determined by the laser comb lines.

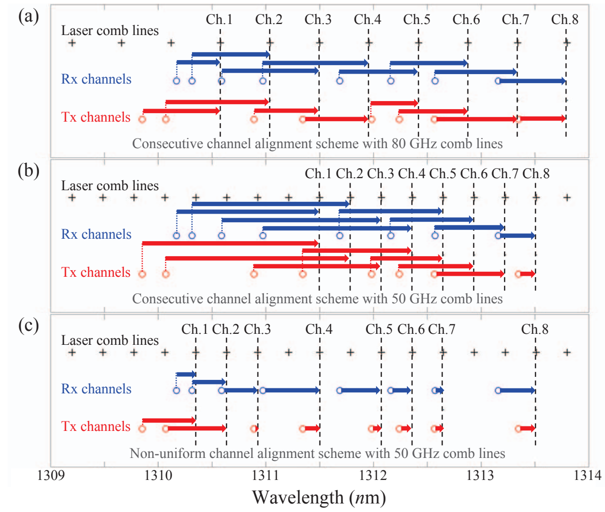

Fig. 3. An illustration of the tuning distance of (a) the consecutive scheme with 80 GHz spaced comb lines, (b) the consecutive scheme with 50 GHz spaced comb lines, and (c) the proposed non-uniform scheme with 50 GHz spaced comb lines. The microring channels are of 80 GHz spacing with variations added on top.

QD comb lasers which span ∼10 nm range have been reported [3], and further increase of the laser spectrum range is expected in the near future [20]. For the extreme case of 50 nm FSR projected in some literature, multiple comb lasers can be combined [17], [18]. It is therefore assumed that the FSR of the microrings can be fully covered by the spectrum of either one or multiple comb lasers. A smaller comb spacing results in more comb lines within a given FSR.

Recent high-efficiency QD comb lasers have achieved up to 7-9 dBm per comb line at ∼20% WPE [3]. It is noteworthy that in addition to the maximum laser power, the optical nonlinearities of the microrings and the silicon waveguides also limit the optical power that can be injected into the transceiver [17], [18], [21]. In brief, any system configuration that requires over 5 dBm optical power per channel or over 20 dBm optical power per waveguide is considered invalid.

IV. Channel Alignment Schemes

Due to the nature of thermal tuning, the spectrum of the microrings can only be red-shifted. Fig. 3(a) illustrates the mechanism of the commonly used consecutive channel alignment scheme, where the circles represent the resonance wavelengths of the microrings as fabricated, and the dashed lines represent the allocated channels. The group of consecutive channels are selected such that the total tuning distance of the microrings

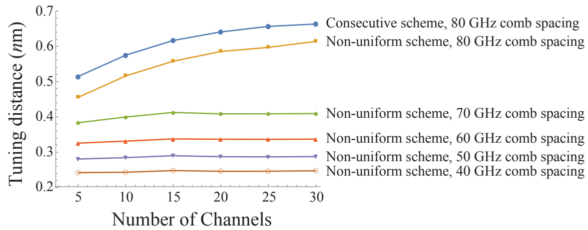

Fig. 4. Average tuning distance per microring for various channel counts using both alignment schemes. The microring channels are of 80 GHz spacing with variations added on top.

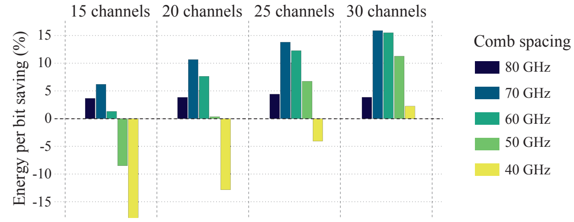

Fig. 5. Saving on system energy per bit under different channel counts using the proposed channel alignment scheme compared to using the consecutive scheme.

is minimized, and each resonance wavelength is only red-shifted. Under this scheme, the utilization of denser comb lines (as in Fig. 3(b)) would pile the allocated channels to the right, causing the tuning distance to increase. As a result, the consecutive channel alignment scheme by default assumes a comb laser with the same channel spacing as the microrings. In order to eliminate such restriction, we propose a non-uniform channel alignment scheme where the usage of consecutive laser comb lines are not mandatory. As illustrated in Fig. 3(c), the proposed scheme aligns each pair of microrings in the Tx and the Rx to the next available laser comb line to their right. The result is a non-uniform distribution of the channels which allows the existence of unused laser comb lines in between.

Fig. 4 illustrates the average tuning distance per microring at various channel counts using both alignment schemes. The results are averaged over synthetic data of 1000 transceivers. For microrings with 80 GHz channel spacing, our scheme with 40-80 GHz spaced laser comb lines always reduces the average tuning distance compared to the consecutive channel alignment scheme. It is also observed that the channel count dependency of the tuning distance can be eliminated by using our scheme with laser comb spacing smaller than 80 GHz. The availability of extra comb lines buffers the wavelength variation of one microring, and mitigates its influence on the channel selection of neighboring microrings.

Our non-uniform channel alignment scheme reduces the required tuning distance of the microrings at the cost of some power wasted in unused laser comb lines. An interesting trade-off therefore arises in terms of the overall energy efficiency of the transceiver link, demonstrated by the following case study. The power consumption of the link is computed assuming a 0.15 nm/mW tuning efficiency [22], and a 10 Gb/s per channel data rate. The overall energy efficiency of the system is computed as the total power consumption over the aggregated data rate for each configuration. The energy efficiency is measured in pJ/b, for which the smaller the value the better.

Fig. 5 shows the saving on the overall energy per bit of the system using our channel alignment scheme. Both the laser comb spacing and the number of channels play their parts in the aforementioned trade-off. For a larger channel count (and thus a higher aggregated data rate), the energy per bit contributed by the laser is reduced, and denser comb lines can be utilized without compromising the overall system energy efficiency. The biggest energy per bit saving, however, does not require aggressively dense comb lines. In this particular example, a comb laser with 70 GHz comb spacing best exploits the proposed scheme in all channel count configurations for microrings designed with 80 GHz channel spacing.

V. Design Space Exploration

We conducted a case study for design space exploration with the laser comb spacing incorporated as a design parameter, seeking the most energy-efficient system configuration at a target aggregated data rate. Since the microrings modeled in this study are based on fabricated devices with a moderate FSR, the purpose of the exploration is not to push the limit of the highest attainable aggregated data rate, but rather to observe the pattern of the optimal design w.r.t. various system configurations. In addition to the laser comb spacing and the transceiver channel count, this study also takes into consideration the projected future advancements in microring and comb laser designs, by varying the microring tuning efficiency and the laser WPE. The per channel data rate is calculated as the target aggregated data rate over the number of channels. The microring channel spacing is fixed at 80 GHz in accordance to the developed process variation model.

Simulations are conducted for various aggregated data rates, and exploration results for 100 Gb/s and 200 Gb/s are summarized in Fig. 6. The overall energy per bit of the transceiver link is illustrated with contour plots color coded from yellow (highest pJ/bit) to blue (lowest pJ/bit). The system configuration that leads to the lowest energy per bit value is marked with a smiley sign in each contour plot.

We observed that the optimal designs in all cases utilize laser comb lines that are denser than the microring channels. The effectiveness of our proposed scheme is therefore validated. The proposed scheme scales well with the target aggregated data rate, as well as the projected future advancements in the microring tuning efficiency and the laser WPE.

As the system configuration changes, the optimal design occurs at a different point in each contour plot. In order to provide general guidelines to the designers of DWDM silicon photonic transceivers, we attribute the various factors affecting the optimal design to two generalized properties of the optical link, namely the *tuning power dominance* and the *laser power dominance*. A low tuning efficiency is a contributor to the tuning power dominance of the system energy per bit, while a low WPE contributes to the laser power dominance. Increasing the target aggregated data rate requires a larger power budget from the laser, which also increace the laser power dominance of the system. Fig. 6 shows that the reduction of tuning power dominance causes the optimal design to drift upper right, which encourages the usage of a larger channel count (lower date rate per channel) and a larger comb spacing. Meanwhile, the reduction of laser power dominance renders

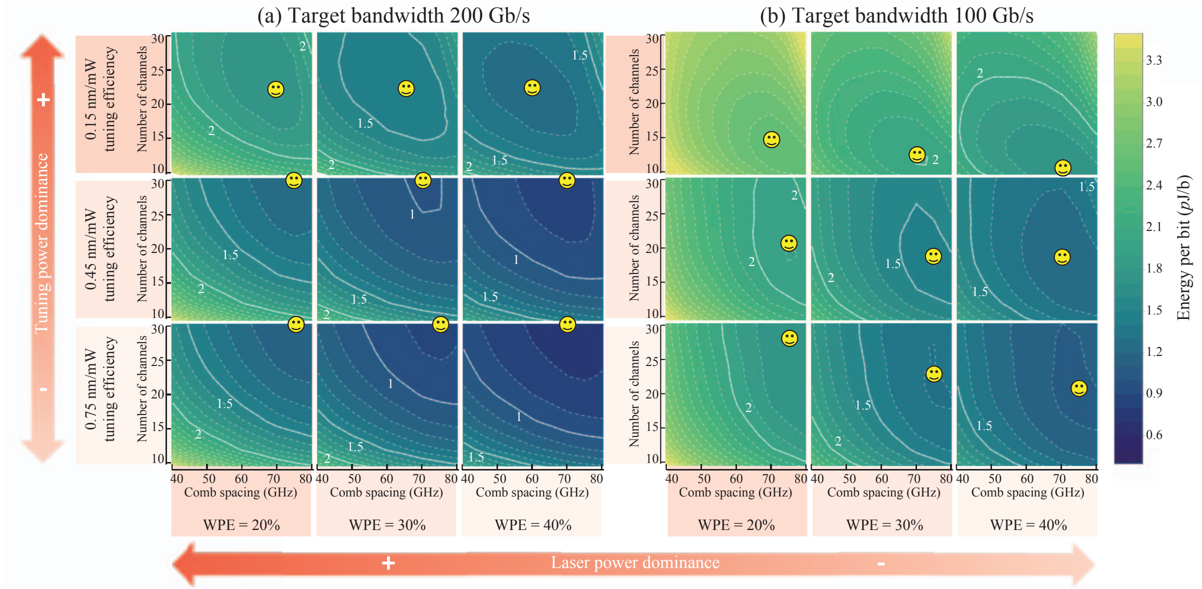

Fig. 6. Design space exploration using the non-uniform channel alignment scheme with a target aggregated data rate of (a) 200 Gb/s, and (b) 100 Gb/s. The smiley sign in each subplot stands for the configuration that leads to the lowest energy per bit value.

the optimal design to drift down, which encourages a smaller channel count. In short, the case study demonstrates how the expanded design space can lead to a more energy-efficient design of DWDM optical transceivers by manipulating the trade-off between the tuning power and the laser power.

VI. Conclusion

In this study, we propose a non-uniform channel alignment scheme for comb laser-driven microring-based optical transceivers. The proposed scheme reduces the average microring tuning power in the presence of laser comb lines that are denser than the microring channels. By exploring the trade-off between the tuning power and the laser power, the overall energy efficiency of the transceiver can be improved. Our scheme allows the laser comb spacing to be added to the design space of DWDM silicon photonic transceivers. A case study for design space exploration validated the effectiveness and scalability of the proposed scheme. Patterns of the optimal design under various system configurations are observed and summarized to guide the energy-efficient design of future DWDM silicon photonic transceivers.

Acknowledgment

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References

[1] R. G. Beausoleil *et al.*, "Photonic architectures for high-performance data centers," *IEEE JSTQE*, 2013.
[2] R. G. Beausoleil, "Large-scale integrated photonics for high-performance interconnects," *J. Emerg. Technol. Comput. Syst.*, Jul. 2011.
[3] D. Livshits *et al.*, "High efficiency diode comb-laser for dwdm optical interconnects," in *Optical Interconnects Conference*. IEEE, May 2014.
[4] X. Zheng *et al.*, "A 33mw 100gbps cmos silicon photonic wdm transmitter using off-chip laser sources," in *OFC*. OSA, 2013.
[5] C.-H. Chen *et al.*, "A comb laser-driven dwdm silicon photonic transmitter based on microring modulators," *Opt. Express*, 2015.
[6] C.-H. Chen *et al.*, "Concurrent multi-channel transmission of a dwdm silicon photonic transmitter based on a comb laser and microring modulators," in *International Conference on Photonics in Switching (PS)*, 2015.
[7] M. A. Seyedi *et al.*, "Concurrent dwdm transmission with ring modulators driven by a comb laser with 50ghz channel spacing," in *OptoElectronics and Communications Conference (OECC)*, 2016.
[8] Q. Xu *et al.*, "Cascaded silicon micro-ring modulators for wdm optical interconnection," *Opt. Express*, Oct 2006.
[9] S. Manipatruni *et al.*, "Ultra high bandwidth wdm using silicon microring modulators," *Opt. Express*, Aug. 2010.
[10] Y. Liu *et al.*, "Ultra-compact 320 gb/s and 160 gb/s wdm transmitters based on silicon microrings," in *OFC*, 2014.
[11] A. V. Krishnamoorthy *et al.*, "Exploiting cmos manufacturing to reduce tuning requirements for resonant optical devices," *IEEE Photonics Journal*, 2011.
[12] M. Georgas *et al.*, "Addressing link-level design tradeoffs for integrated photonic interconnects," in *IEEE Custom Integrated Circuits Conference (CICC)*. IEEE, Sep. 2011.
[13] R. Polster *et al.*, "Efficiency optimization of silicon photonic links in 65-nm cmos and 28-nm fdsoi technology nodes," *IEEE Trans. VLSI Systems*, 2016.
[14] Y. Zheng *et al.*, "Power-efficient calibration and reconfiguration for optical network-on-chip," *JOCN*, Dec. 2012.
[15] Y. Zheng *et al.*, "Post-fabrication reconfiguration for power-optimized tuning of optically connected multi-core systems," in *Proc. ASP-DAC*, 2012.
[16] R. Wu *et al.*, "Pairing of microring-based silicon photonic transceivers for tuning power optimization," in *ASP-DAC*, Jan. 2018.
[17] M. Bahadori *et al.*, "Comprehensive design space exploration of silicon photonic interconnects," *IEEE JLT*, Jun. 2016.
[18] M. Bahadori *et al.*, "Energy-performance optimized design of silicon photonic interconnection networks for high-performance computing," in *DATE*. IEEE, Mar. 2017.
[19] K. Bergman, "Nanophotonic interconnection networks for performance-energy optimized computing," in *IEEE International Interconnect Technology Conference*, 2012.
[20] G. L. Wojcik *et al.*, "A single comb laser source for short reach wdm interconnects," in *Proc. SPIE*, Feb. 2009.
[21] Q. Li *et al.*, "Experimental characterization of the optical-power upper bound in a silicon microring modulator," in *Optical Interconnects Conference*. IEEE, May 2012.
[22] K. Yu *et al.*, "A 25 gb/s hybrid-integrated silicon photonic source-synchronous receiver with microring wavelength stabilization," *IEEE J. Solid-State Circuits*, Sep. 2016.