Paving the Path to Spatially Multiplexed Coherent Ising Machines

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***Abstract*—Solving computation problems in time- and energy-efficient ways becomes an important task in the advent of artificial intelligence and virtualization. Emerging computational paradigms, such as quantum computing and Ising machines are promising candidates to challenge these goals. Ising machines, in particular, benefit significantly from the high-speed capabilities of photonic technologies. Most Ising machine implementations rely on time-multiplexing, while spatial multiplexing promises greater performance and better integration. We analyse the thermal challenges of building a silicon-based spatially multiplexed coherent Ising machine. Our results clearly state the constraints and thermal solutions for such machines.**

***Index Terms*—photonic, microring resonator, Ising machine, open source modeling, thermal simulation.**

I. Introduction

Coherent Ising machines (CIMs) are an upcoming concept for energy-efficient computing in the field of combinatoric optimization problems. There exist mapping algorithms for several NP-hard problems, including max-cut and graph coloring, which have been successfully implemented and tested [1]. The main working principle of an Ising machine is that a problem is translated into input parameters, i.e. coupling factors between Ising spins. This can be done in polynomial time for problems in the complexity class NP. With these coupling factors, the Ising machine is run by decreasing the temperature model value. That way, the Ising spin combination with the lowest Hamiltonian aka energy level will emerge as the solution of the problem.

One major advantage of CIMs over other quantum-like computing devices is that they do not require cooling to temperatures near absolute zero to achieve quantum-equivalent states. This characteristic makes CIMs potentially suitable for compact implementations with significantly lower energy consumption compared to quantum devices.

Implementing Ising machines in relevant sizes, i.e. in terms of number of Ising spins exhibits certain challenges. While creating a single spin has been demonstrated in different technologies and with different mechanisms, scaling is still a very challenging task.

There are two major paths to implement a scalable Ising machine: (1) time-multiplexing, where a single physical spin-implementation is sufficient and (2) spatial multiplexing with the need of multiple physical spins (Figure 1). For the first option, long, thermally stabilized delay lines are needed to store the spin information for spin coupling. The latter option needs fine-tuned physical spin representations with identical properties. Both options are challenging due to temperature influence and manufacturing tolerances.

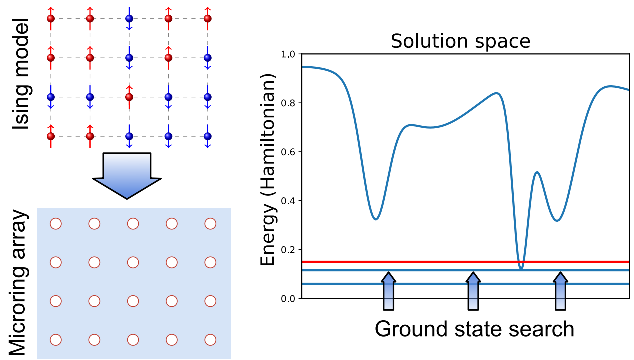

Figure 1. Working principle of a spatially multiplexed coherent Ising machine (CIM) based on microrings. The problem solution is found by a ground state search by slow (adiabatic) increase of the Hamiltonian.

The primary contributions of this paper include:

- A comprehensive analysis of the challenges for scaling Ising machines,
- thermal analyses of spatial multiplexed Ising machines and
- guidelines to microring-based, spatial multiplexed Ising machines.

II. State of the Art

Parts of this section have already been published in [2]. A common method to achieve coherent Ising machines with a large number of spins is time-multiplexing [3]. Typically, a single optical cavity (or resonator) for modeling the Ising spin behavior is combined with a long optical delay line that stores the signal pulses of each spin and a feedback system to model the interaction (or coupling) between the spins. However, this technique necessitates the use of extensive optical waveguides, which scale with the number of spins being simulated. This requirement poses a challenge for integrating such systems into compact devices. An alternative approach is the spatially multiplexed Ising machine, which relies on a network of optical microring resonators [4]. There, each microring

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resonator models an Ising spin by utilizing either degenerate optical parametric oscillations or optical bistability. For further reading, the fundamentals of optical microrings are described in [5].

Recently, silicon nitride (SiN) has become the predominant material for constructing waveguide structures and resonators in CIMs. The primary advantage of SiN is its lower thermo-optic coefficient, which results in reduced temperature dependence of the refractive index. Due to the lack of two-photon absorption (TPA), silicon nitride microresonators have less nonlinear loss and heating compared to silicon when operating in nonlinear regimes. Okawachi et al. [6], demonstrated a pair of coupled optical parametric oscillators (OPOs) in SiN to simulate the ground state of the Ising model.

The use of silicon as a waveguide material enables the seamless integration of additional electronic devices, such as transistors and CMOS gates for signal processing and for electronic control of the photonic devices. Typically, a silicon-on-insulator (SoI) technology is employed for silicon photonics applications. Patterning produces the waveguide structures and electronic control interfaces for the photonic system inside the silicon layer above the buried oxide. In this geometrical arrangement, the interface to the buried oxide serves as reflective surface due to the large difference in refractive indices. However, silicon exhibits a high photon absorption in its intrinsic state due to the presence of free charge carriers, necessitating electronic depletion to enhance its photonic efficiency. This is achieved by creating doped silicon regions beneath the waveguide, which must be electrically connected to form a lateral p-i-n structure with the waveguide situated in the intrinsic region. Electrical signals can then dynamically adjust the optical properties of the waveguide via the p-i-n structure.

Silicon-based photonic integrated circuits (ICs) can benefit significantly from the integration of electronics for sensing, computation and electronic control of the photonic device, all fabricated on a single die. This integration enables compact CIM devices, particularly by sacrificing long delay lines of time-multiplexing designs. To date, these spatially multiplexed CIM devices have primarily been analyzed theoretically [7].

Thermal modeling and simulation has revealed the range of thermal relaxation times of silicon waveguides [8]. Coenen et al. [9] examined the differences in thermal relaxation times during heating and cooling phases. Their study also highlighted the impact of undercuts—partially etched regions beneath photonic structures—on thermal time constants. These undercuts lead to increased heating and cooling time constants. Hence, undercuts are not ideal for Ising machine applications, where low relaxation times are desirable. Further influences on the thermal relaxation times was studied in [2].

Thermal analyses of waveguides and silicon microrings have been performed in previous works [2], [10], but the step towards scaling of these devices is still missing. In particular, mostly thermal properties of distinct photonic components are analyzed, while their mutual interaction has not been studied in-depth.

III. Problem Formulation

There are two major implementation perspectives for large scale Ising machines, which are spatial multiplexing and time multiplexing. The first uses dedicated hardware elements for each Ising spin, the latter utilizes shared physical components but dedicated time slots. The operation constraints for coherent Ising machines are very limiting. In the case of oscillators used for modeling Ising spins, the oscillation frequency has to meet almost exactly the desired value and if multiple oscillators are concerned, those must be tuned to the exact same frequency. To get an insight on the thermal constraints for spatially multiplexed Ising machines, we have to consider the thermo-optic coefficient of silicon and the manufacturing tolerances. The goal is to enable a very narrow resonance frequency.

IV. Preliminary Analyses

We first analyzed the demands for spatially multiplexed coherent Ising machines. Our estimations are based on the temperature-dependent optical properties of silicon, i.e. the refractive index and the thermo-optic coefficient. The temperature-dependent values are shown in Figure 2 with data according to [11]–[13]. Assuming an average refractive

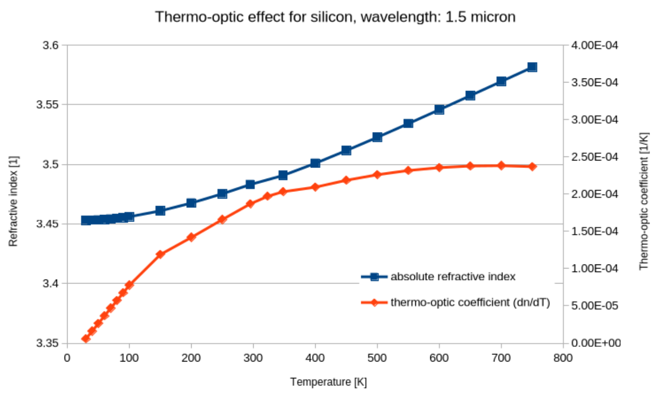

Figure 2. Temperature-dependent optical properties of silicon for infrared light of 1.5 µm wavelength in vacuum (frequency: 200 THz). The upper curve illustrates the absolute refractive index and the lower curve the temperature coefficient of the refractive index. Measurement data from [13], [12] and [11]

index of 3.48 and a thermo-optic coefficient of $2 \times 10^{-4}\,\mathrm{K}^{-1}$ for a wavelength of $1.5\,\mu\mathrm{m}$, we must obtain a temperature precision of 10 to $50\,\mathrm{mK}$, depending on the quality factor of the resonators (range $10^5 \ldots 10^6$), over the full array of spins to restrict the resonance frequency tolerance sufficiently.

As an attempt to find reasonable geometry constraints for the microring array, we simulated the temperature field around a single microring resonator while heat is generated either in the optical waveguide ring itself or in the heater above. We assume that only a certain temperature shift in the location of a neighboring ring resonator is allowed. The geometric structure of a single resonator is illustrated in Figure 3.

The simulations have been performed in Ansys [14]. The temperature result is shown in Figure 7. For an assumed temperature shift of $20\,\mathrm{mK}$, the minimal distance between

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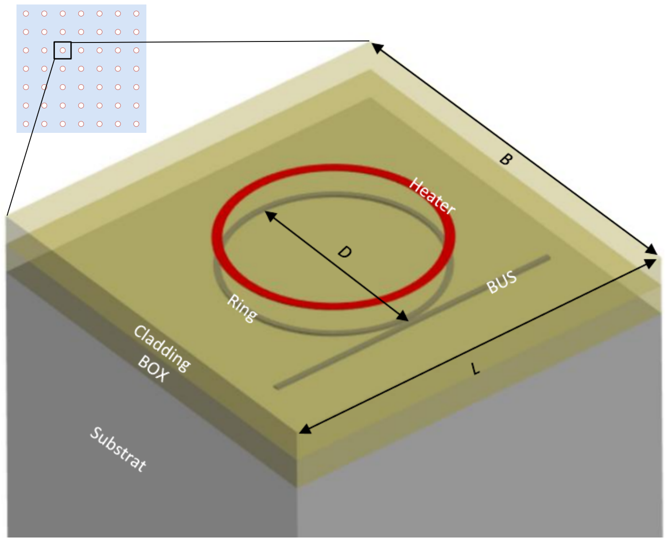

Figure 3. Three-dimensional model of a single microring resonator with associated heater structure for temperature tuning. This structure resembles the major component needed for a single Ising spin.

two resonators is 80 µm, which is four times the diameter of the ring. We use this distance for our modeled microring array. This allows to arrange an array of $200 \times 200 = 40000$ resonators on a die with two centimeter edge length. The number of available spins is almost in the range of time-multiplexed Ising machines that have been demonstrated [3].

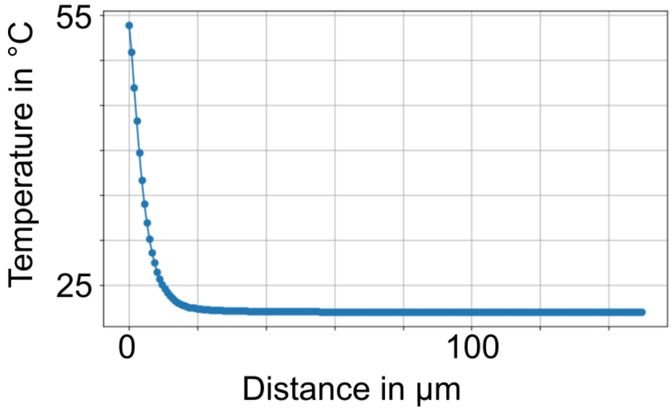

Figure 4. Temperature profile on a lateral radial path from a heated microring

The simulation of the following models were conducted using the open source software Elmer FEM [15], [16]. The models themselves have been constructed with gmsh [17].

V. Experimental Results

The microrings have to be equipped with a heater to account for manufacturing tolerances (cf. Figure 3). Those have to be compensated to achieve a set of quasi-identical microrings without any bias that can be used as an Ising machine. By uniform heating, or just by ordinary operation (heating by optical losses), we end up in a temperature profile as in Figure 5, where a hot spot can be found in the center of the microring array.

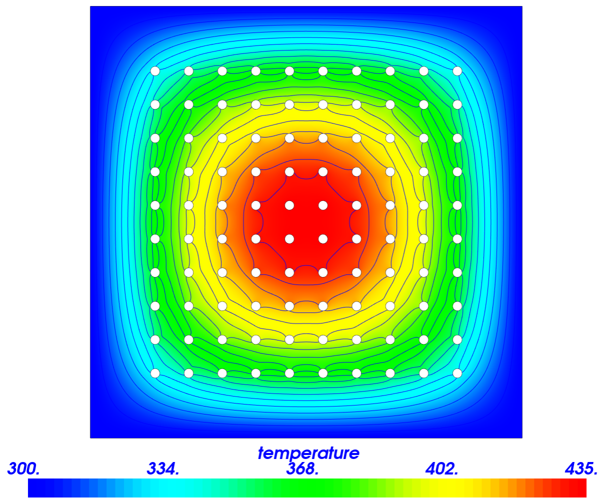

Figure 5. Temperature profile (in K) of a uniformly heated microring array (900 µm by 900 µm. A marked hot spot is visible.

To compensate this effect without active cooling, we have to increase the heating power at the boundaries of the array. A polynomial approach using an eighth-degree function provided very promising results (Figure 6).

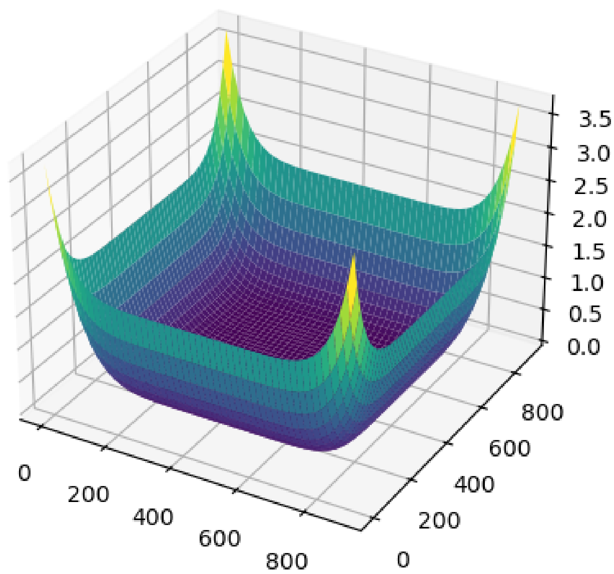

Figure 6. Heating profile as a polynomial approach to compensate the hot spot and create a uniform Temperature profile in the microring array. Dimensions in µm, vertical axis: dimension less weighting factor

Using a polynomial function for weighting the heating power results in a very flat temperature profile over almost the full array of microrings (Figure 7). This profile can be used as

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a baseline, where the spatial temperature is compensated. To equalize the resonators in terms of resonance frequency and to compensate manufacturing tolerances, further adjustments of the individual heating powers will be necessary. While the individual control of heating power is mandantory, the analytic, polynomial preload may not be implemented in the final control algorithm. Its primary goal was to show that the temperature restrictions can be managed in principle.

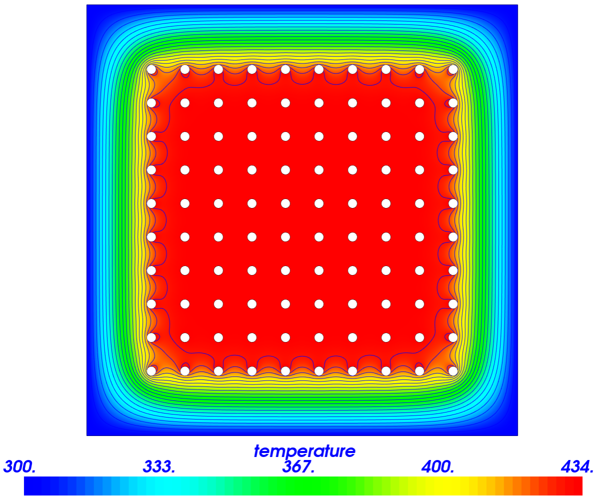

Figure 7. Temperature profile of a microring array with hotspot compensation using the heating profile of Figure 6. The boundary rings are still not completely temperature compensated, which can be solved by either increasing their heating power further or by a dummy heater ring outside the microring array.

VI. Conclusion and Outlook

This paper reviews and analyses the thermal implications in the task of creating a spatially multiplexed coherent Ising machine based on silicon microrings. We conclude that the found spacing constraints allow the integration of a scaled Ising machine on a compact chip size of around two centimeters edge length. Optical routing may nevertheless lead to congestion in the center region of the array. This can be eased using electrical spin coupling and corresponding electrical routing outside the optical routing plane. Switching to technologies with multiple optical routing layers would also be an option. We have shown that an equalized temperature profile can be achieved by thermal heaters above the microrings. Edge effects and individualized tolerance compensation will have to be accounted for.

Acknowledgements

The authors want to thank Kambiz Jamshidi and Menglong He for their collaboration and valuable contributions. This work was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – 466323332.

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