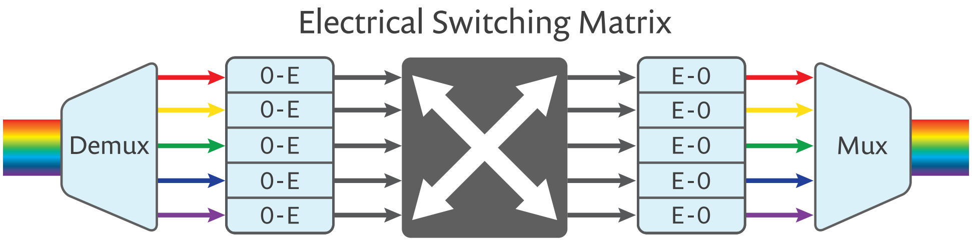
DESIGNING ENERGY- EFFICIENT PHOTONIC SWITCHES TO SUPPORT GROWING NETWORK TRAFFIC

Thermo-optic silicon photonic switches are under development at Huawei Technologies Canada for the communications and high-performance computing industries. Design optimization via numerical analysis aims to minimize power consumption and maximize switching speed.

By **JENNIFER SEGUI**

ALL-OPTICAL NETWORKS WERE ENVISIONED DECADES AGO because of their potential for high transmission speeds to address the ever-increasing demands on network performance. Photonic switches are already widely deployed throughout cities and long-distance networks, while experiments in data centers and high performance computing are ongoing. Huawei Technologies Canada is radically improving critical optical components, such as photonic switches, using silicon photonics (SiPh).

Optical networks use waves of light to transmit data, for example, when a phone call is placed or a search request or email is handled. To route the data at various points in the network, the optical signal is traditionally converted back to an electrical signal, switched, and then converted again to an optical signal as shown in Figure 1. Converting the signal uses large, power-hungry equipment, which adds latency while each packet is converted. In comparison, photonic switches do not convert the signal format. Hence photonic switches are often faster, smaller, and more energy efficient.



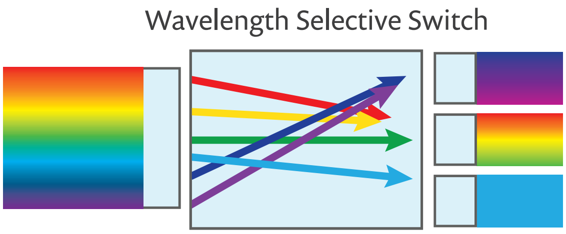


Figure 1. Optical fibers and switches can carry light of one or more wavelengths at the same time. Top: the optical signal is converted to an electrical signal for routing, then electrical signals are converted back to optical signals before being sent out on another optical fiber. Bottom: an all-optical switch does not require the additional electrical-optical conversion stages.

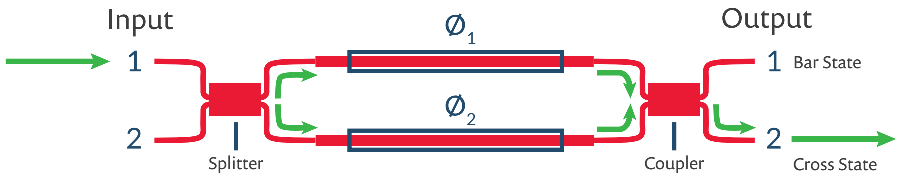


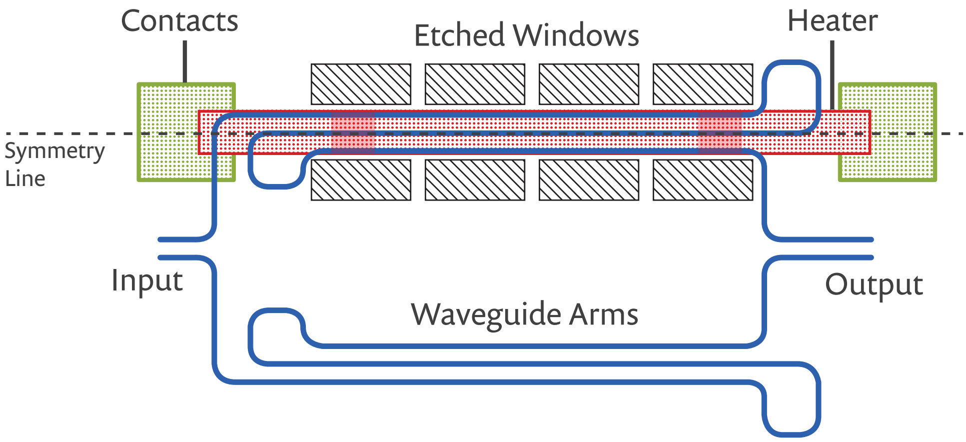
Figure 2. In a Mach-Zehnder interferometer, light entering an input waveguide is split onto two arms, where the waves will experience a phase shift depending on the optical properties of each arm. At the output, the coupled waves will undergo constructive and destructive interference representing the cross and bar states of an optical switch. The path in green shows the default switch state.

Existing photonic switches, however, are bulky and expensive, and are made of many hand-assembled components. To address the issue, Huawei is developing circuits using integrated SiPh technology. Optical circuits are made in CMOS chip foundries with silicon waveguides about 0.5 micrometers across, which is possible because silicon is transparent at the signal wavelengths.

At Huawei, they are prototyping some of the most complex silicon photonic circuits in the world, relying on an integrated design environment. Highly accurate numerical physics models are fine-tuned through iterative prototyping cycles, while photonic circuit layout software ensures first-time-right chip design. The thermal performance of the thermo-optic SiPh switch is a core part of this design workflow.

» ROUTING DATA WITH THERMO-OPTIC SWITCHES BASED ON PHASE SHIFT

THE THERMO-OPTIC SWITCH under development is a silicon photonic Mach-Zehnder (MZ) interferometer, which has a



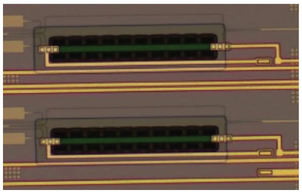


Figure 3. Diagram of a thermo-optic Mach-Zehnder phase shifter with thermal undercut, at top, where a resistive heater (pink) located above one of the waveguide arms (blue) is used to change the index of refraction causing a phase shift in the propagating light wave. The photo at bottom shows the heated waveguide as fabricated.

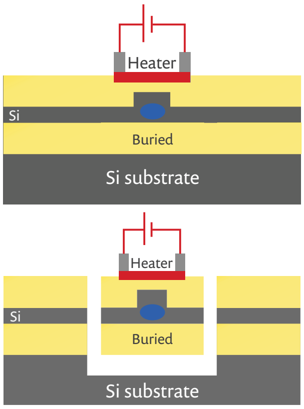


Figure 4. Cross-sectional view of the heated waveguide arm of a thermo-optic Mach Zehnder switch without (top) and with (bottom) thermal undercut. The thermal undercut isolates the waveguide and heater reducing wasteful heat transfer to the surrounding material.

cross state and a bar state. By default, the MZ shown in Figure 2 is in the cross state. A light wave arriving at an input (e.g. input 1) is split and travels along both arms. The light from the two arms interferes at the output coupler. Because of the relative phase of the light from the two arms, all of the light comes out of output 2.

A thermally induced phase shift provides a way to flip the switch state. To switch a thermo-optic MZ to its bar state, one arm of the MZ is heated. This changes the refractive index of the waveguide, creating a π phase shift in the light propagating in that arm. Interference causes the light to come out of output 1, carrying data toward a different destination. By combining a large number of these switch cells on one chip, a large switch matrix is created.

The MZ switch design implemented by Huawei is presented in Figure 3, where light enters the switch and is divided between the two folded waveguide arms, which are represented by blue lines. Above one arm is a titanium nitride (TiN) resistive heater, indicated by the pink shaded region in the figure. Applying a voltage to the electrical contacts causes the heater to increase the temperature of the underlying waveguide to produce a π phase shift, which changes the switch state. The triple-folded waveguide increases the interaction length between the heater and waveguide, thus improving the efficiency by a factor of three.

The heated waveguide arm of the thermo-optic switch in Figure 3 is a suspended structure, where the surrounding cladding material is etched away, forming a thermal undercut. A cross-sectional view of the waveguide with and without thermal undercut is shown in Figure 4. The thermal undercut prevents heat conduction to the underlying substrate, allowing the heater to raise the temperature of the buried waveguide 23 times more efficiently, and therefore consume 96 percent less power.

» THERMAL ANALYSIS AND DESIGN OPTIMIZATION

THE REQUIREMENTS ON POWER consumption, switching speed, and physical size, together with the manufacturing design rules of the thermal undercut, combine to create a significant optimization problem for the implementation of thermo-optic MZ switches. To arrive at a final design, thermal analysis in COMSOL Multiphysics® software provides an efficient means to quantitatively evaluate new designs before manufacturing physical prototypes.

"Our move toward large-scale product development demands thorough optimization work, where every mW of power consumption counts," says Dritan Celo, a senior research engineer at Huawei. Therefore, COMSOL® software was added to the integrated design environment for

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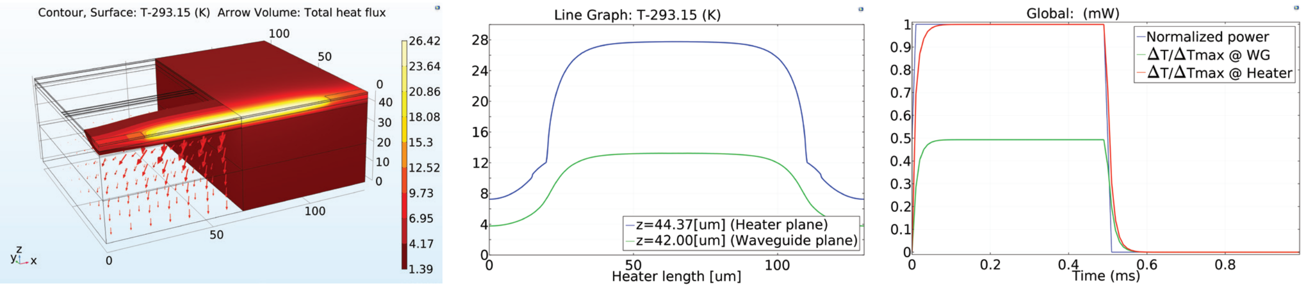
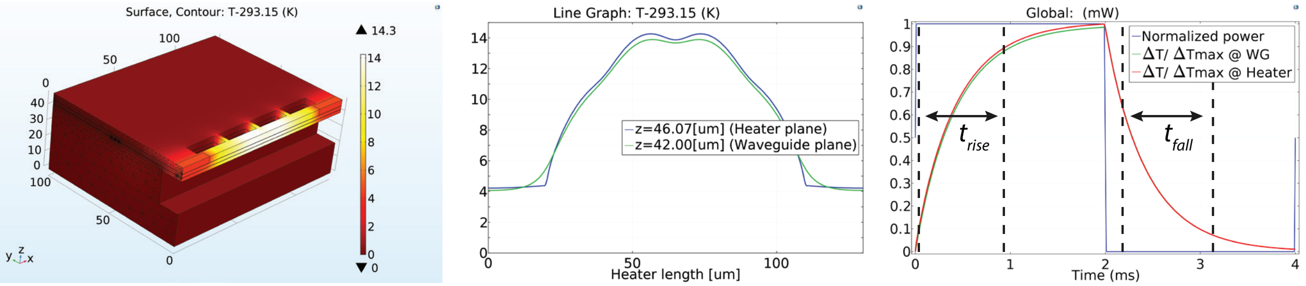


Without Thermal Undercut



With Thermal Undercut

Figure 5. COMSOL Multiphysics® software model of a thermo-optic switch without (top) and with (bottom) thermal undercut. Plots show the steady state temperature distribution (left), temperature difference between heater and waveguide (middle), and transient analysis indicating time required for the waveguide to reach target temperature (right).

silicon photonic devices.

For example, thermal analysis is used to quantify the performance of different thermo-optic designs, both with and without thermal undercut, which is an important consideration since undercut adds additional steps to the manufacturing process. Additionally, while using a thermal undercut can improve the energy efficiency of a device, there is a decrease in switching speed, hence a device geometry with undercut is suited only for certain applications.

The device geometry shown in Figure 3 was implemented in COMSOL® software, both with and without using a thermal undercut. To reduce the computation time required for steady state thermal analysis of each design, half symmetry was used as indicated by the dashed black line in Figure 3, and the resulting model geometry is shown at left in Figure 5. Silicon waveguides that are 100s of micrometers in length are buried in silica glass on top of a silicon substrate. Material properties assigned to each domain in the model were chosen from options that are already available in the software. Since SiPh structures have high-aspect ratios of 1000:1, COMSOL Multiphysics® meshing algorithms were critical for fast and accurate modeling.

Heat transfer in solids is modeled throughout the device geometry, with insulating boundary conditions defined on the surface passivation layer and thermal undercut boundaries when present.

The titanium nitride heater in the heated waveguide arm is defined as the heat source in the switch model, and simulation results reveal how much applied thermal power is required to produce a π phase shift for a given design. To produce a π phase shift, the waveguide temperature must change by 13.3 Kelvin, which is a value determined from optical test measurements.

Steady state analysis of the thermo-optic SiPh switch demonstrates a 23x reduction in the amount of power required to achieve a π phase shift when a thermal undercut is included in the design. The temperature distribution is shown at left in Figure 5 for each device geometry. The plots in the middle depict the temperature difference between the heater and waveguide, demonstrating the extent of heat loss to the surrounding materials in devices without undercut.

A difference of 0.2 Kelvin was achieved in the design with undercut, compared to a 13 Kelvin difference without. Transient analysis, using quarter symmetry to further reduce computation time, provides information on how long it takes to tune the waveguide to the desired temperature and phase, which limits the cross/bar switching speed of the device. Although devices with undercut are more energy efficient, they do not tune as quickly as devices without undercut, as demonstrated by the rise and fall times at right in Figure 5.

The validated steady state and transient models are also critical for evaluating the thickness of the silica glass, overall size of an individual MZ switch, and effect of a cooling passivation layer on top of the device, thus enabling an application to maximally benefit from reduced power consumption.

» PACKING THOUSANDS OF SWITCHES ONTO A SINGLE CHIP

ALTHOUGH THE FOCUS of the heat transfer simulations is to optimize a single thermo-optic MZ switch, in actual practice, they are not found alone, but used in large switching matrices as shown in Figure 6. Huawei's matrix is designed to prevent optical crosstalk, which ensures that the optical signals out of the switch are very clean. The architecture at left in Figure 6 represents a 32x32 SiPh switch matrix containing 448 2x2 thermo-optic MZ switch cells. A light path passes through one cell in each column, and the path is defined by applying the appropriate cross or bar drive power to those cells. Supplying power to a switch raises the underlying waveguide temperate and generates the necessary π phase shift that allows a signal to propagate along a chosen path.

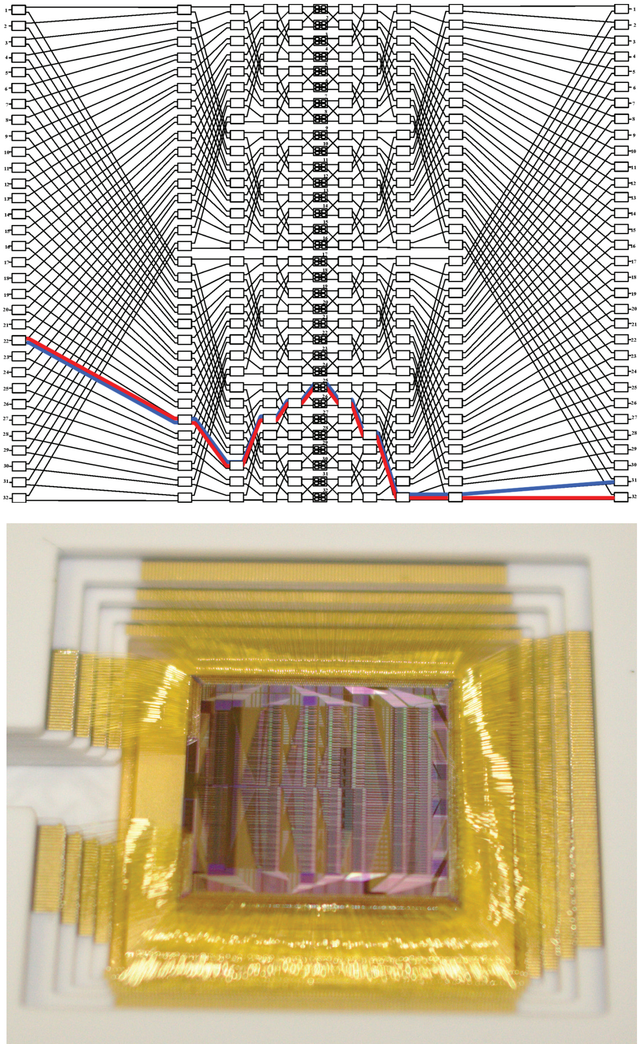
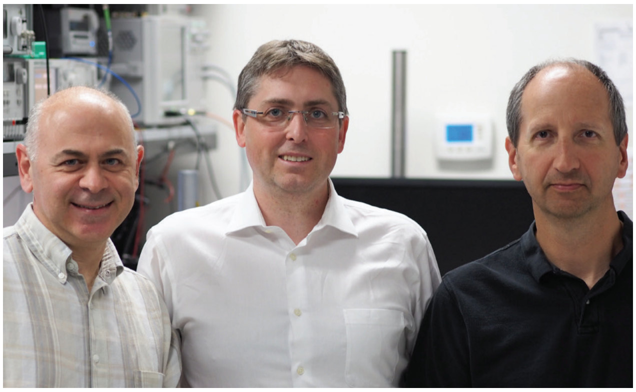


Figure 6. A 32x32 switch matrix with 448 2x2 thermo-optic MZ cells (top), and the fabricated prototype with on-chip monitor photodiodes with each cell (bottom).

A fabricated prototype of the 32x32 switch matrix is shown at right in Figure 6, and was produced at a CMOS foundry that specializes in the manufacture of SiPh devices, including the thermal undercut technique. The prototype also includes on-chip monitor photodiodes for each cell to determine the cross/bar drive current, and represents an important advance in their work.

Entering the prototyping and large-scale product development phase opens up new challenges, which require designers to divide their time between the R&D facilities at Huawei and the foundry. "Thermal performance is a small, but important piece of the very large puzzle that represents the device design workflow," explains Celo. "Looking toward large-scale product development, fabricating a 128x128 SiPh switch with thousands of MZ cells on a single die that consumes no more than 50 watts of power, which may be used in many different environments, raises questions about mechanical stability. Structural analysis of the packaged switch has now become a focus, and numerical simulation in COMSOL® software will again prove useful to optimize its design." ◎



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