# OTemp: Optical Thermal Effect Modeling Platform User Manual

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Optical interconnect (including on-chip and on-board optical interconnect) is emerging communication technique that can potentially offer ultra-high communication bandwidth and low latency to multiprocessor systems. Thermal sensitivity is an intrinsic characteristic as well as a potential issue of photonic devices used in optical interconnects. Chip temperature fluctuates spatially, and the steady-state temperature can vary significantly across a chip under typical operating conditions. As a result of thermo-optic effect, temperature variations can potentially cause power efficiency degradation. Optical interconnect thermal models at system level are required to fully understand these challenges. In this manual, we will introduce OTemp (Figure 1), an optical thermal effect modeling platform for both WDM-based and single-wavelength optical links in optical interconnects. OTemp is based on the system-level optical interconnect thermal models presented in our previous work. OTemp is a C++ based program to analyze the thermal-aware power consumption as well as the optical power loss for optical links under temperature variations. The inputs to this tool include the photonic devices parameters, the optical link configurations, and the temperature range. The component library of OTemp includes optical link components such as the BOSE (basic optical switching element), BOME (basic optical modulation element), and BOFE (basic optical filter element). OTemp models the thermal effects in component level, and then arrives at the system-level thermal model according to the relationship between different components in an optical link.

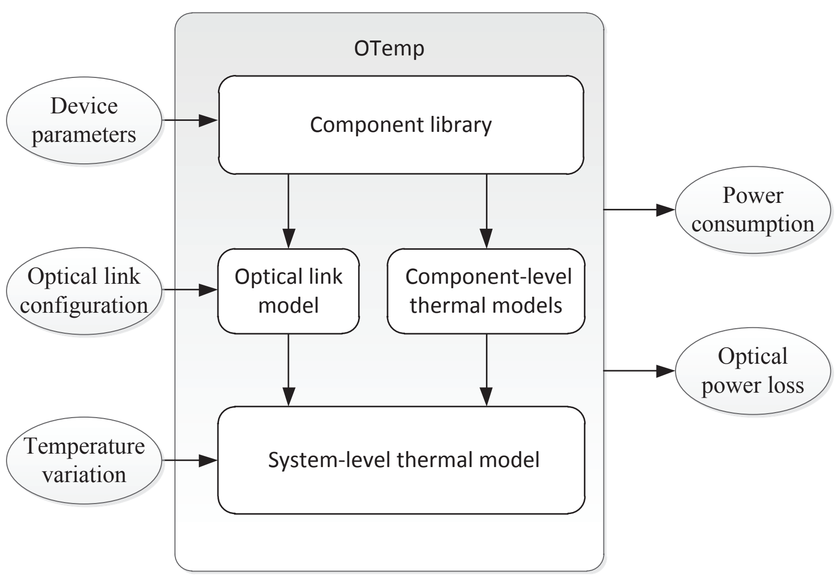



Fig. 1: The flow chart of OTemp: the optical thermal effect modeling platform

# I. THERMAL SENSITIVITY OF PHOTONIC DEVICES

The absolute temperature and temperature fluctuations across the chip die have been major concerns in chip design and packaging because a high temperature could cause performance degradation and even functional failures in CMOS circuits. Steady-state chip temperature varies spatially because of the non-uniform power densities across the chip as well as the limited thermal conductivity of the die and packaging materials. As a result of thermo-optic effect, material refractive index is temperature dependent and follows Equation (1), where $n_0$ is the refractive index at room temperature, $dn/dT$ is the thermo-optic coefficient of the material, and $\Delta T$ is the temperature variation. Since refractive index is an important device parameter, the thermo-optic effect will cause changes in photonic device characteristics.

$$n = n_0 + \frac{dn}{dT}\Delta T \tag{1}$$

## A. *Optical transmitters*

Optical transmitters convert electrical signals into optical signals by either directly modulating the driving current of laser source, or using an optical modulator. VCSELs are a good candidate for optical interconnect laser source because of the low power consumption, high modulation bandwidth and manufacturing advantages. The characteristics of VCSELs are sensitive to temperature changes. If using off-chip laser equipped with temperature control unit, the laser can be set at a fixed wavelength but it consumes extra power. In OTemp, we assume VCSELs as the laser source and consider their thermal variations when developing the optical interconnect thermal model.

As in Equation (2), the emission wavelength $\lambda_{VCSEL}$ is determined by the cavity resonance, where $n_{ave}$ is the spatially averaged refractive index of the laser cavity, $l_{VCSEL}$ is the cavity length, and $m_{VCSEL}$ is the resonance order.

$$l_{VCSEL} \cdot n_{ave} = m_{VCSEL} \cdot \lambda_{VCSEL}/2 \tag{2}$$

The lasing wavelength of VCSELs red-shift approximately linearly with temperature, which can be calculated by Equation (3). $\lambda_{VCSEL\_0}$ is the VCSEL lasing wavelength at room temperature $T_0$, and $\rho_{VCSEL}$ is defined as the temperature-dependent wavelength shift coefficient of VCSELs.

$$\lambda_{VCSEL} = \lambda_{VCSEL\_0} + \rho_{VCSEL}(T_{VCSEL} - T_0) \tag{3}$$

Besides the temperature-dependent wavelength shift, the power efficiency of VCSELs degrades with increasing temperature as a result of thermal effects on the threshold current and slope efficiency. The output power of VCSEL degrades at higher operating temperatures. Assuming that the VCSEL is driven by current $I$ which is above the threshold but before the point where the output power starts to decrease with current, we can express the output optical power $P_{out}$ by Equation (4), where $T_{VCSEL}$ is the VCSEL operating temperature, $\alpha$ is the minimum threshold current, $\beta$ is a coefficient related to the gain properties, $T_{th}$ is the temperature at which the cavity resonance is spectrally aligned with the peak gain, $\varepsilon$ is the slope efficiency at $0^oC$, and $\gamma$ is a positive coefficient.

$$P_{out} = (I - \alpha - \beta(T_{VCSEL} - T_{th})^2)(\varepsilon - \gamma \cdot T_{VCSEL}) \tag{4}$$

VCSEL power consumption can be calculated as *UI*, where $U$ is the bias voltage and $I$ is the driving current. Equation 5 shows the bias voltage, where $U_{slope}$ is the slope of the U(V)-I(mA) characteristic curve of the VCSEL, and $U_{th}$ is the intercept of the U(V)-I(mA) characteristic curve of the VCSEL.

$$U = U_{slope} \cdot I + U_{th} \tag{5}$$

### B. Microresonator-based add-drop filters

On the optical path between the transmitter and receiver, multiple switching elements switch optical signals in stages onto a series of optical waveguides until reaching their destination. Microresonator-based add-drop filters have been widely used as the switching elements to perform the switching function in optical interconnect. The peak resonant wavelength $\lambda_{MR}$ of a microresonator obeys the relationship in Equation (6), where $l_{MR}$ is the one-round length of the ring, $m_{MR}$ is an integer indicating the order of the resonance, and $n_{eff}$ is the effective index of the waveguide mode involved in the resonance.

$$l_{MR} \cdot n_{eff} = m_{MR} \cdot \lambda_{MR} \tag{6}$$

With a constant $l_{MR}$ and $m_{MR}$, the peak resonant wavelength $\lambda_{MR}$ will change in proportion with $n_{eff}$. Since $n_{eff}$ changes with the temperature, the peak resonant wavelength will also vary with the temperature. Both theoretical analysis and experiment results confirm a linear relationship (Equation (7)) between the resonant wavelength shift and temperature, where $\lambda_{MR\_0}$ is the resonant wavelength at room temperature $T_0$ and $\rho_{MR}$ is the temperature-dependent wavelength shift coefficient of the microresonator.

$$\lambda_{MR} = \lambda_{MR\_0} + \rho_{MR}(T_{MR} - T_0) \tag{7}$$

Microresonator-based add-drop filter has a Lorentzian power transfer function which is peaked at the resonant wavelength $\lambda_{MR}$. For optical signals at wavelength $\lambda_s$, the drop-port power transfer can be expressed as Equation (8), where $2\delta$ is the 3-dB bandwidth of the drop-port power transfer spectrum, $\kappa_e^2$ is the fraction of power coupling between the input waveguide and the ring, $\kappa_d^2$ is the fraction of power coupling between the drop waveguide and the ring, and $\kappa_p^2$ is the power loss per round-trip of the ring. When $\kappa_d^2 + \kappa_e^2 \gg \kappa_p^2$, nearly full power transfer can be achieved at the peak resonance point, and the microresonator will exhibit a low insertion loss.

$$\frac{P_{drop}}{P_{in}} = (\frac{2\kappa_e \kappa_d}{\kappa_e^2 + \kappa_d^2 + \kappa_p^2})^2 \cdot \frac{\delta^2}{(\lambda_s - \lambda_{MR})^2 + \delta^2} \tag{8}$$

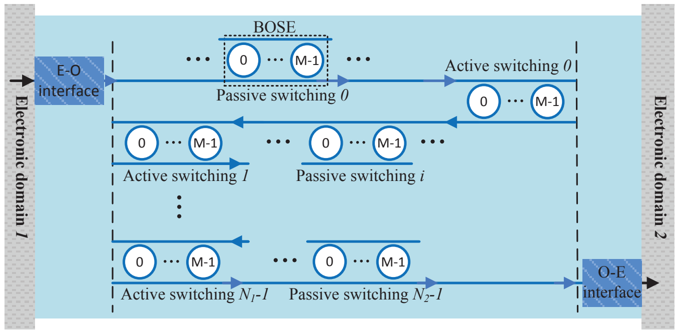
### C. Optical waveguide and receiver

Waveguide propagation loss is much less sensitive to temperature compared to the insertion loss of high-Q switching elements. We assume the waveguide propagation loss variation is negligible. Optical receivers use photodetectors for optical-to-electrical conversion. Based on related studies, we assume that the sensitivity of the optical receiver does not change with the operating temperature in our optical interconnect thermal model.

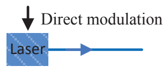
## II. The System-Level Thermal Model for a WDM-Based Optical Link

Most optical interconnect architectures employ photonic devices which can be integrated with existing CMOS-based processor cores either through CMOS-compatible fabrication processes or bonding technologies. An M-wavelength WDM-based optical link in optical interconnect is generally composed of an E-O interface, an optical path, and an O-E interface (Figure 2). The E-O interface converts electrical signals into optical signals by directly modulating the driving current of the laser source, or using microresonator-based modulators to modulate the continuous wave (CW) signal. At the receiver side, the O-E interface includes photodetectors which convert optical signals into electrical signals used by processors or memories in electronic domains. A typical receiver also includes transimpedance amplifier (TIA) and limiting amplifier (LA) circuits for current-to-voltage conversion and voltage amplification.

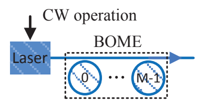
The basic optical modulation element (BOME) consists of an array of M optical modulators. We assume the M-wavelength WDM laser sources at room temperature $T_0$ are at $\lambda_0, \lambda_1, \cdots \lambda_{M-1}$, with a channel spacing of $s$. The off-state BOME resonate at $\lambda_0, \lambda_1, \cdots \lambda_{M-1}$, by which the laser signals are modulated to data $0$. When the BOME is turned on by forward-bias voltage, the resonance of each ring is blue-shifted, and the laser signals would be modulated to data $1$. On the optical path between the



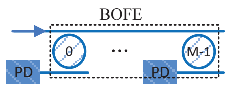

(a) An overview of the M-wavelength WDM-based optical link in optical interconnect




(b) E-O interface with direct modulation




(c) E-O interface with separate modulators




(d) O-E interface

Fig. 2: An overview of the M-wavelength WDM-based optical link connecting two electronic domains

transmitter and receiver, basic optical switching element (BOSEs) switch optical signals in stages onto a series of optical waveguides until reaching the destination. The basic optical filter element (BOFE) is used at the receiver to filter out the M wavelengths to before reaching photodetectors

### A. *BOSE Insertion Loss*

In the basic optical switching element (BOSE), the overall amplitude transmission from the input port to the drop port can be found by application of the recursive formula in Equation (9), where the recursion starts with $f_0 = r_0$. $r_n$ and $t_n^i$ are the amplitude transmission from the input port to the drop port and through port respectively for ring *n* in isolation (n=0,1,...,M-1). $t_n^o$ is the amplitude transmission from the add port to the drop port. $\theta_n = 2\pi L_n/\lambda$ is the phase delay along the waveguide between the reference planes of ring $n$ and ring $n+1$, where $L_n$ is the spacing between the two rings and $\lambda$ is the wavelength in free space. $\tau = 2\pi R n_g/c$ is the round-trip propagation time in microresonator. We assume that microresonators in the array are coupled to waveguides with $\kappa_e^2 = \kappa_d^2 = \kappa^2$. $\omega_n = 2\pi c/\lambda_n$ is the on-state resonance frequency of the ring *n*.

$$f_n = r_n - \frac{t_n^i t_n^o}{r_n - f_{n-1}^{-1} exp(j2\theta_{n-1})} \tag{9}$$

$$\omega_n = \frac{2\pi c}{\lambda_n + \rho_{MR} \cdot \Delta T} \tag{10}$$

$$r_n = \frac{2\kappa^2}{j2\tau(\omega - \omega_n) + (2\kappa^2 + \kappa_p^2)} \tag{11}$$

$$t_n^i = t_n^o = \frac{j2\tau(\omega - \omega_n) + \kappa_p^2}{j2\tau(\omega - \omega_n) + (2\kappa^2 + \kappa_p^2)} \tag{12}$$

For the input signal with wavelength $\lambda$, the overall power transfer at the drop port of the M-ring BOSE is $|f_{M-1}|^2$. The insertion loss in an active switching stage is as Equation (13). If the microresonator is turned on by carrier injection, there is an additional insertion loss. Some related works indicated that the addition insertion loss can be estimated as $1.28dB/nm \cdot b$, where $b$ is the blue shift when the microresonator is turned on by carrier injection.

$$L_{BOSE\_active} = -10log|f_{M-1}|^2 \tag{13}$$

### B. BOME Insertion Loss

At room temperature, when the M-wavelength BOME is turned off (modulating 0), they are resonating at the laser source wavelengths with spacing $s$. When the M-wavelength BOME is turned on (modulating 1), they are blue-shifted by $b$. The power transfer at the output port of a modulator is as $T_{modulator}$.

$$T_{modulator} = \frac{b^2 + \delta^2 \cdot (\frac{\kappa^2-\kappa_p^2}{\kappa^2+\kappa_p^2})^2}{b^2+\delta^2} \tag{14}$$

If the temperature increases from room temperature $T_0$ by $\Delta T = T - T_0$, the resonance wavelength of the M-wavelength BOME red-shift by $\rho_{MR} \cdot \Delta T$. For wavelength-0 optical signal, the worst-case insertion loss caused the M-wavelength BOME is

$$L_{BOME\_0} = \sum_{i=0}^{M-1} 10log \frac{(\frac{i \cdot s - b + \rho_{MR} \cdot \Delta T}{\delta})^2 + 1}{(\frac{i \cdot s - b + \rho_{MR} \cdot \Delta T}{\delta})^2 + (\frac{\kappa^2-\kappa_p^2}{\kappa^2+\kappa_p^2})^2} \tag{15}$$

For the optical signal with wavelength $\lambda_x, x \in [0, M-1]$, the worst-case insertion loss caused the M-wavelength BOME is

$$L_{BOME\_x} = \sum_{i=0}^{M-x-1} 10log \frac{(\frac{i \cdot s - b + \rho_{MR} \cdot \Delta T}{\delta})^2 + 1}{(\frac{i \cdot s - b + \rho_{MR} \cdot \Delta T}{\delta})^2 + (\frac{\kappa^2-\kappa_p^2}{\kappa^2+\kappa_p^2})^2} + \sum_{j=1}^{x} 10log \frac{(\frac{j \cdot s - \rho_{MR} \cdot \Delta T}{\delta})^2 + 1}{(\frac{j \cdot s - \rho_{MR} \cdot \Delta T}{\delta})^2 + (\frac{\kappa^2-\kappa_p^2}{\kappa^2+\kappa_p^2})^2} \tag{16}$$

### C. BOFE insertion loss

The basic optical filter element (BOFE) is used at the receiver to filter out the M wavelengths to photodetectors. The $i_{th}$ ($i \in [0, M-1]$) ring in the BOFE is corresponding to the laser wavelength $\lambda_0$. If the temperature of BOFE increases from room temperature $T_0$ by $\Delta T = T - T_0$, the resonance wavelength of the M-wavelength BOFE red-shift by $\rho_{MR} \cdot \Delta T$. For the optical signal of $\lambda_0$, the optical power loss (Equation (17)) is just the drop-port insertion loss of the $0_{th}$ ring in the BOFE, where $\delta$ is half of the 3-dB bandwidth of the drop-port power transfer spectrum of the rings in the BOFE, $\kappa^2$ is the fraction of power coupling between the input/output waveguides and the rings, and $\kappa_p^2$ is the power loss per round-trip of the rings.

$$L_{BOFE\_0} = 10log((\frac{2\kappa^2 + \kappa_p^2}{2\kappa^2})^2 \cdot (\frac{(\rho_{MR}\Delta T)^2 + \delta^2}{\delta^2})) \tag{17}$$

For the optical signal with wavelength $\lambda_x, x \in [1, M-1]$, the worst-case insertion loss caused the M-wavelength BOME is

$$L_{BOFE\_x} = 10log((\frac{2\kappa^2 + \kappa_p^2}{2\kappa^2})^2 \cdot (\frac{(\rho_{MR}\Delta T)^2 + \delta^2}{\delta^2})) + \sum_{i=0}^{x-1} 10log \frac{((x-i) \cdot s + \rho_{MR}\Delta T)^2 + \delta^2}{((x-i) \cdot s + \rho_{MR}\Delta T)^2 + \delta^2 \cdot (\frac{\kappa_p^2}{2\kappa^2+\kappa_p^2})^2} \tag{18}$$

### D. System-level thermal model

To ensure that optical interconnect functions properly, a necessary condition is that the optical signal power received by the receiver of an optical link should not be lower than the receiver sensitivity $S_{RX}$. We model the condition in Equation (19), where $P_{TX}$ is the output power of the optical transmitter on a link, $L_{total}$ is the total optical power loss in the path, and $S_{RX}$ is the sensitivity of the receiver.

$$P_{TX} - L_{total} \geq S_{RX} \tag{19}$$

For an M-wavelength WDM-based optical link, we can get the optical interconnect thermal model in Equation (20). If using off-chip VCSELs as the laser sources, $T_{VCSEL}$ can be fixed by using temperature control. If using on-chip VCSELs as the laser sources, $T_{VCSEL}$ varies in the temperature range $[T_{min}, T_{max}]$.

Under a high power loss in the optical path caused by temperature fluctuations, more input power would be needed by the transmitter to guarantee enough optical power reaching the receiver. We assume that the number of active switching and passive switching is $N_1$ and $N_2$ respectively. The total optical power loss to optical signals with wavelength $\lambda_x, x \in [0, M-1]$ is the summation of insertion loss of each module, where $L_{BOME\_x}$ is the insertion loss in the modulation stage (Equation (16)), $L_{BOSE\_active\_i}$ is the insertion loss in the $i_{th}$ active switching stage (Equation (13)), $L_{BOSE\_parking\_j}$ is the insertion loss in the $j_{th}$ parking switching stage, $L_{WG}$ is the waveguide propagation loss in the path, and $L_{BOFE\_x}$ is the insertion loss of BOFE optical signals with wavelength $\lambda_x$ (Equation (18)). The thermal-aware optical power received at the end of the link can be calculated by the left side of Equation (20).

$$10log((I-\alpha-\beta(T_{VCSEL}-T_{th})^2)(\varepsilon-\gamma\cdot T_{VCSEL}))-L_{BOME\_x}-\sum_{i=0}^{N_1-1}L_{BOSE\_active\_k} \\ -\sum_{j=0}^{N_2-1}L_{BOSE\_parking\_j}-L_{BOFE\_x}-L_{WG}\geq S_{RX} \quad (20)$$

The by-default setting of BOSEs and BOME and BOFE are according to the laser wavelengths at room temperature $T_0$. For thermal-based adjustment with guard rings for channel remapping, the tuning distance $d$ for each ring is as Equation (21).

$$d=\lceil\frac{\rho_{MR}\cdot\Delta T}{s}\rceil\cdot s-\rho_{MR}\cdot\Delta T \quad (21)$$

In order to use thermal-based adjustment without guard rings, since the thermal tuning can only do red-shift of wavelength, the resonance wavelength of a microresonator should always be no larger than the corresponding laser wavelength, even under the maximum temperature. This can be guaranteed by setting $\lambda_{MR\_0}$ as the condition shown in Equation (22), where $\lambda_{MR\_0}$ is the resonance wavelength of the $0_{th}$ ring in the M-wavelength BOSE at room temperature $T_0$, and $\lambda_0$ is the $0_{th}$ laser wavelength at room temperature.

$$\lambda_{MR\_0}=\lambda_0-\rho_{MR}\cdot\Delta T_{max} \quad (22)$$

In this case, even under the maximum temperature variation, each microresonator can be adjusted to the corresponding laser wavelength by thermal-based adjustment. The tuning distance is as Equation (23).

$$d=\rho_{MR}\cdot(\Delta T_{max}-\Delta T) \quad (23)$$

## III. For analysis of Single-Wavelength Based Optical Link

For the analyze of thermal effects in single-wavelength optical links, we assume to use direct-modulated VCSEL as the laser source and the number of active switching stages in the link is $N$. The thermal model of a single-wavelength optical link is presented in Equation (24). $L_{WG}$ is the optical power loss due to the waveguides on the optical link.

$$10log((I-\alpha-\beta(T_{VCSEL}-T_{th})^2)\cdot(\varepsilon-\gamma\cdot T_{VCSEL})) \\ -\sum_{i=1}^{N}10log((\frac{2\kappa^2+\kappa_p^2}{2\kappa^2})^2\cdot(\frac{\delta^2+(\lambda_{VCSEL\_0}+\rho_{VCSEL}(T_{VCSEL}-T_0)-\lambda_{MR\_0}-\rho_{MR}(T_{MR_i}-T_0))^2}{\delta^2} \\ -L_{WG}\geq S_{RX} \quad (24)$$

A closer study of the thermal model reveals several thermal properties of optical interconnect. First, the number of switching stages in an optical link can dramatically change the thermal-induced power consumption. Second, initial device settings such as $\lambda_{MR\_0}$ can affect the thermal-induced power consumption. Third, the 3-dB bandwidth of MR is an important factor regarding the thermal-induced additional optical power loss in the switching stages.

The by-default setting of microresonator wavelength at room temperature is $\lambda_{MR\_0} = \lambda_{VCSEL\_0}$. The additional optical power loss under temperature variation can be reduced if we set $\lambda_{MR\_0}$ according to the optimal setting (Equation (25)).

$$\lambda_{MR\_0\_optimal} = \lambda_{VCSEL\_0} + \frac{(\rho_{VCSEL} - \rho_{MR})}{2} \cdot (T_{max} + T_{min} - 2T_0) \tag{25}$$

## IV. OTEMP FILE FORMAT

### A. The parameter file

The parameter file is as shown in Table I. The program would load the file to get the photonic devices parameters.

TABLE I: The format of the parameter file.

```
T_0                     //the room temperature, in degree
lambda_VCSEL_0          //VCSEL wavelength at room temperature, in nm
row_VCSEL               //VCSEL temperature-dependent wavelength shift, in nm/degree
alpha                   //VCSEL minimum threshold current, in mA
belta                   //a coefficient related to the VCSEL threshold current
T_th                    //the temperature at which the VCSEL threshold current is minimum
epsilon                 //the slope efficiency of VCSEL at 0 degree
garma                   //a coefficient related to the VCSEL slope efficiency
L_MR_resonance_peak     //MR insertion loss at the resonance peak, in dB
row_MR                  //MR temperature-dependent wavelength shift, in nm/degree
fabrication_sigma       //Gaussian distribution SD, fabrication error
P_MR_on                 //the average power consumed for turning on MR, in mW
Modulation_speed        //the modulation speed of the VCSEL, in Gbps
S_RX                    //the receiver sensitivity, in dBm
L_propagate             //waveguide propagation loss, 0.17dB/mm
L_crossing              //waveguide crossing loss, 0.12dB/crossing
link_length             //length of the optical link, in mm,
crossing_number         //the number of waveguide crossing in the optical link
E_serializer            //the serializer energy consumption, in pJ/bit
E_driver                //VCSEL driver energy consumption, in pJ/bit
E_PD                    //the photodetector energy consumption, in pJ/bit
E_deserializer          //the deserializer energy consumption, in pJ/bit
E_TIA_LA                //the TIA-LA energy consumption, in pJ/bit
U_slope                 //the slope of the U(V)-I(mA) characteristic curve of the VCSEL
U_th                    //the intercept of the U(V)-I(mA) characteristic curve of the VCSEL
P_thermaltuning         //power consumption of thermal-based adjustment per microresonator, in mW/nm
lambda                  //laser wavelength[M-1-i]=lambda-i*channel_spacing, in nm
elec_switch_off_on      //positive, blue-shift when turned on by electronic-based switching, in nm
thermal_switch_off_on   //negative, red-shift when turned on by thermal-based switching, in nm
modulation_0_1          //positive, blue-shift of electronic-based modulation to data "1", in nm
lambda_misplace_factor  //misplacement_region/half_3dB_bandwidth, "3" for 0.46dB drop
P_modulator_data_0      //modulator output power for data 0
```

### B. The configuration files

The configurations for a WDM-based optical link (Table II) includes choosing whether to use on-chip or off-chip VCSEL as the laser source (by-default: use off-chip VCSEL); choosing whether to use BOME for modulation or use direct-modulated VCSEL (by-default: use BOME for modulation); choosing whether to use guard rings for channel remapping in thermal-based adjustment (by-default: with guard rings and channel remapping); choosing whether to use the by-default setting or the optimal setting of $\lambda_{MR\_0}$ (by-default: $\lambda_{MR\_0} = \lambda_0$); the WDM channel spacing (by-default: 1nm), the number of WDM wavelength (by-default: 8); the switching mechanism for BOSE (by-fault: electronic-based switching), the number of

TABLE II: The format of the configuration file for WDM-based thermal analysis.

```
flag_OnChipVCSEL        //"1" for using on-chip VCSEL; "0" for using off-chip VCSEL
flag_BOME               //"1" for using BOME; "0" for using direct-modulated VCSEL
flag_guard_ring         //"1" for using guard rings for thermal adjustment; "0" for w/o guard rings
flag_lambada_MR_0       //"0" for using the by-default setting of MRs; "1" for using the optimal setting
channel_spacing         //WDM channel spacing, in nm
M                       //the number of WDM wavelength
flag_switching          //"1" for electronic-based switching; "0" for thermal-based switching
N_active_BOSE           //the number of active BOSE stages
N_park_BOSE             //the number of parking BOSE stages
Q                       //quality factor of the MRs used in the WDM-based optical link
```

active BOSE in the link (by-default: 3); the number of parking BOSE in the link (by-default: 10); and the quality factor of the microresonators used in optical components (by-default: 5000).

The configuration file for single-wavelength based analysis (Table III) includes the choosing of on-chip or off-chip VCSEL (by-default ”1”, the current version only supports for On-chip VSCEL), the number of active switching stages (by-default ”3” if using passive-routing), and the 3-dB bandwidth (by-default ”3.1” nm, which is pretty large) of the microresonator. The program would load the file to get the configurations for the single-wavelength based optical link.

TABLE III: The format of the configuration file for single-wavelength based thermal analysis.

```
flag_OnChipVCSEL        //"1" for using on-chip VCSEL; "0" for using off-chip VCSEL
N_active                //the number of active switching stages in the optical link
bandwidth               //the 3-dB bandwidth of microresonator
```

### *C. The output files*

For analyze of WDM-based optical links, the outputs (Table IV and Table V) include the worst-case and average thermal-aware power consumption with or without thermal-based adjustments. If using on-chip VCSELs as the laser source, the total power consumption is equal to the on-chip power consumption. If using off-chip VCSELs as the laser source, we are more concerned with the on-chip power consumption. The output file includes both of the total power consumption and on-chip power consumption. The worst-case analysis are conducted among all possible thermal maps where the maximum temperature is $T_{max}$ and the minimum temperature is $T_{min}$. The average analysis considers all possible temperature conditions and get the average power consumption based on the uniform temperature distribution ranging from $T_{max}$ to $T_{min}$. If using off-chip VCSELs as the WDM laser source, we assume the VCSELs work with temperature control units and the lasers temperature is fixed at room temperature $T_0$. If using on-chip VCSELs as the laser source, we assume the VCSELs temperature varies in the temperature range $[T_{min}, T_{min}]$. For the case with thermal-based adjustment, two scenarios are analyzed including using the thermal-based adjustment together with guard rings for channel remapping, or using the thermal-based adjustment without channel remapping. The by-default setting of $\lambda_{MR\_0}$ (resonance wavelength of the $0_{th}$ ring in the M-wavelength BOSE and BOFE and BOME at room temperature $T_0$) is equal to $\lambda_0$ (the $0_{th}$ WDM laser wavelength at room temperature). If using thermal-based adjustment without channel remapping, since the thermal tuning can only do red-shift of wavelength, the resonance wavelength of a microresonator should always be no larger than the corresponding laser wavelength, even under the maximum temperature. This can be guaranteed by setting $\lambda_{MR\_0}$ as Equation (22), according to which $\lambda_{MR\_0}$ is lower than $\lambda_0$ and the difference is determined by the maximum temperature variation $\Delta T_{max}$. The output results include both of the total power consumption and the on-chip power consumption. If using on-chip laser as the laser source, the total power consumption is equal to the on-chip power consumption. If using off-chip laser as the laser source, the on-chip power consumption does not include the power consumed by the laser source itself.

TABLE IV: The format of the output file for WDM-based worst-case thermal analysis.

```
Total_E_w/o_thermal_adjust_worst   //worst-case, total power w/o thermal-based adjustment
Total_E_w_thermal_ajust_worst      //worst-case, total power w/ thermal-based adjustment
OnChip_E_w/o_thermal_adjust_worst  //worst-case, on-chip power w/o thermal-based adjustment
OnChip_E_w_thermal_ajust_worst     //worst-case, on-chip power w/ thermal-based adjustment
```

TABLE V: The format of the output file for WDM-based average thermal analysis.

```
Total_E_w/o_thermal_adjust_average   // total power w/o thermal-based adjustment average
Total_E_w_thermal_ajust_average      // total power w/ thermal-based adjustment average
OnChip_E_w/o_thermal_adjust_average  // on-chip power w/o thermal-based adjustment average
OnChip_E_w_thermal_ajust_average     // on-chip power w/ thermal-based adjustment average
```

For analyze of single-wavelength optical links, the outputs include the worst-case (Table VI) and average-case (Table VII) thermal-aware power consumption under different combinations of low-temperature-dependence techniques, such as the optimal setting of $\lambda_{MR\_0}$ (Equation (25)), thermal-based adjustment for the active switching stages, and the use of athermal microresonators. The worst-case and average-case analysis are conducted among all possible thermal maps where the temperature varying spatially between $T_{min}$ and $T_{max}$. If using on-chip VCSELs as the laser source, the worst-case occurs when the VCSEL works at the maximum on-chip temperature $T_{max}$ while microresonators at all the active switching stages work at the minimum on-chip temperature $T_{min}$. In this case, the laser power efficiency would be the worst, and the wavelength mismatch between the laser and the active switching stages would also be the worst. The average-case power consumption is calculated as the mathematical expectation of the power consumption, while assuming that the temperatures of on-chip VCSEL and all microresonators are all uniformly distributed between $T_{min}$ and $T_{max}$.

TABLE VI: The format of the output file for single-wavelength based worst-case thermal analysis.

```
E_default_w/o_thermal_worst   //worst-case, lambda_MR_0=lambda_VCSEL_0, w/o thermal adjustment
E_default_w/_thermal_worst    //worst-case, lambda_MR_0=lambda_VCSEL_0, with thermal adjustment
E_default_w/_athermal_worst   //worst-case, lambda_MR_0=lambda_VCSEL_0, with athermal MRs
E_optimal_w/o_thermal_worst   //worst-case, lambda_MR_0 is optimal, w/o thermal adjustment
E_optimal_w/_thermal_worst    //worst-case, lambda_MR_0 is optimal, with thermal adjustment
E_optimal_w/_athermal_worst   //worst-case, lambda_MR_0 is optimal, with athermal MRs
```

TABLE VII: The format of the output file for single-wavelength based average-case thermal analysis.

```
E_default_w/o_thermal_average //average-case, lambda_MR_0=lambda_VCSEL_0, w/o thermal adjustment
E_default_w/_thermal_average  //average-case, lambda_MR_0=lambda_VCSEL_0, with thermal adjustment
E_default_w/_athermal         //average-case, lambda_MR_0=lambda_VCSEL_0, with athermal MRs
E_optimal_w/o_thermal_average //average-case, lambda_MR_0 is optimal, w/o thermal adjustment
E_optimal_w/_thermal_average  //average-case, lambda_MR_0 is optimal, with thermal adjustment
E_optimal_w/_athermal_average //average-case, lambda_MR_0 is optimal, with athermal MRs
```

## V. Usage instructions

To compile the software, use g++ OTemp.cpp -o OTemp -lm
To run the software, use ./OTemp T_min T_max flag_WDM
T_min is the minimum temperature
T_max is the maximum temperature
flag_WDM ”0” for single-wavelength based, ”1” for WDM-based thermal analysis