

Thermal-Drift-Aware Adaptive Wavelength Stabilization Model for Silicon-Photonic Optical Communication Systems

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Abstract

The increasing integration density and operating speed of silicon-photonic communication devices have intensified the influence of thermo-optic effects on wavelength stability, resonance alignment, optical transmission, and communication reliability. Temperature variations modify the effective refractive index and physical dimensions of photonic structures, resulting in resonance displacement and degradation of wavelength-dependent optical performance. This paper proposes a Thermo-Optical Resonance Tracking (TORT) model for adaptive wavelength stabilization in integrated optical communication systems. The proposed formulation establishes a coupled mathematical relationship between effective refractive index, thermal expansion, resonant wavelength, optical transmission, temperature-dependent optical loss, absorbed power, and thermal dynamics. A closed thermo-optical feedback mechanism is developed to describe the interaction $T \rightarrow n_{eff} \rightarrow \lambda_r \rightarrow H \rightarrow P_{abs} \rightarrow T$. An adaptive wavelength-correction equation is subsequently introduced to compensate for temperature-induced resonance displacement. Furthermore, a unified optimization function incorporating wavelength error, optical loss, absorbed power, temperature deviation, and bit-error performance is formulated. A local thermal stability condition is derived to identify stable operating regions and prevent excessive thermo-optical feedback. The proposed model provides a compact analytical framework for evaluating and stabilizing wavelength-sensitive silicon-photonic devices under dynamically varying thermal conditions. The formulation applies to microring resonators, resonant modulators, optical filters, wavelength-division-multiplexed transceivers, and other integrated optoelectronic communication platforms for reliable next-generation optical communication applications.

Keywords: Silicon photonics, thermo-optic effect, wavelength stabilization, microring resonator, optical communication, thermal drift, adaptive control, photonic integrated circuits, resonance tracking, wavelength-division multiplexing

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INTRODUCTION

Silicon photonics has emerged as an important technology for high-capacity optical communication because it enables compact, low-power, high-bandwidth, and highly integrated photonic devices compatible with semiconductor manufacturing processes. Silicon-photonic platforms are increasingly being investigated for optical interconnects, data-center communication, wavelength-division multiplexing (WDM), coherent communication, and photonic signal processing. However, the high integration density

of photonic and electronic components introduces thermal interactions that can significantly affect wavelength-sensitive devices. Microring resonators, resonant modulators, and optical filters depend strongly on the effective refractive index and optical path length, both of which vary with temperature. Recent studies on silicon photonics have demonstrated the importance of thermal management, wavelength control, and photonic integration for maintaining stable optical operation [1, 2].

The resonance condition of an integrated photonic resonator is governed by the relationship between the effective refractive index, optical path length, and resonant wavelength. Even a small temperature variation can shift the resonance wavelength and cause wavelength misalignment in WDM systems. Such a shift can modify the transmission spectrum, increase the insertion loss, generate crosstalk between adjacent wavelength channels, and degrade the signal quality. Therefore, thermal effects are particularly important in densely integrated photonic circuits, where multiple optical and electronic components operate within a limited physical area [3, 4].

Several researchers have investigated the thermal tuning and stabilization mechanisms for silicon photonic devices. Thermal control based on integrated heaters can compensate for resonance displacement; however, continuous heater operation may increase power consumption and generate additional heat. Alternative approaches based on feedback control, thermal isolation, thermal design, and advanced photonic structures have been explored [5–7]. The increasing use of silicon photonics for high-speed communication has further increased the importance of rapid and accurate resonance tracking because environmental and self-heating conditions can vary dynamically during operation [8, 9]. The problem becomes more complex when optical absorption is incorporated into the thermal model. Absorbed optical power increases the device temperature, whereas temperature changes modify the refractive index and resonance wavelength. The resulting feedback mechanism can alter the optical transmission and consequently change the absorbed power again. A model that treats temperature and optical resonance independently cannot fully represent this coupled behavior. Recent developments in programmable photonic circuits and integrated optical computing have further emphasized the need for reliable thermal control of wavelength-sensitive photonic elements [10–12]. To address this issue, this study proposes a thermo-optical resonance tracking (TORT) mathematical framework for adaptive wavelength stabilization. The main contribution is a unified formulation that couples thermo-optic refractive-index variation, thermal expansion, resonance displacement, optical transmission, temperature-dependent optical loss, absorbed power, and thermal dynamics. Subsequently, an adaptive wavelength-correction mechanism is introduced to reduce resonance error under temperature variations. A multi-objective optimization function is also formulated by simultaneously considering wavelength error, optical loss, absorbed power, thermal deviation, and communication performance. Finally, a local thermal stability criterion is derived to identify conditions under which the thermo-optical feedback remains stable. The goal of the proposed framework is to provide a methodical analytical foundation for comprehending the linked optical and thermal behavior of integrated silicon-photonics communication systems. The TORT model clearly considers the interplay between temperature change, resonance displacement, optical transmission, absorption, and thermal feedback, in contrast to methods that mainly concentrate on heater-based tuning or isolated thermal compensation. This integrated representation offers a foundation for determining stable and effective operating areas and for the assessment of wavelength stability under dynamically changing operating conditions. When accurate wavelength control is necessary for dependable high-speed optical communication systems, the framework can facilitate the analysis of microring resonators, resonant modulators, optical filters, and WDM transceivers.

PROPOSED THERMO-OPTICAL RESONANCE TRACKING MODEL

Consider a silicon-photonics resonant device with optical path length L , effective refractive index n_{eff} , and resonance wavelength λ_r . The fundamental resonance condition is

$$m\lambda_r = n_{\text{eff}}(T)L(T), \quad (1)$$

where m is the integer resonance order.

The temperature-dependent effective refractive index is expressed as

$$n_{\text{eff}}(T) = n_0 + \frac{dn_{\text{eff}}}{dT}(T - T_0), \quad (2)$$

where n_0 is the effective refractive index at reference temperature T_0 , and dn_{eff}/dT is the thermo-optic coefficient.

The thermal expansion of the optical path is represented by

$$L(T) = L_0[1 + \alpha_L(T - T_0)], \quad (3)$$

where L_0 is the reference optical path length and α_L is the thermal-expansion coefficient.

Differentiation of Equation (1) produces the temperature-induced wavelength shift

$$\left[\frac{d\lambda_r}{dT} = \lambda_r \left[\frac{1}{n_{\text{eff}}} \frac{dn_{\text{eff}}}{dT} + \alpha_L \right] \right] \quad (4)$$

which represents the fundamental thermo-optic sensitivity of the device.

Temperature-Dependent Optical Transmission

The optical phase accumulated within the resonant structure is expressed as

$$\phi(\lambda, T) = \frac{2\pi n_{\text{eff}}(T)L(T)}{\lambda}. \quad (5)$$

A generalized normalized transmission function can then be written as

$$H(\lambda, T) = \frac{(1-a)^2 + 4a \sin^2(\phi/2)}{(1-a)^2 + 4a \sin^2(\phi/2) + \delta^2}, \quad (6)$$

where a is the round-trip amplitude factor and δ represents the effective coupling/loss parameter.

The temperature-dependent optical attenuation is defined as

$$\alpha_{\text{opt}}(T) = \alpha_0 + \alpha_T(T - T_0), \quad (7)$$

where α_0 is the reference optical attenuation and α_T is the temperature coefficient.

The received optical power is therefore

$$P_r = P_t e^{-\alpha_{\text{opt}}(T)L} H(\lambda, T) \quad (8)$$

where P_t is the transmitted optical power and P_r is the received optical power.

Thermo-Optical Feedback Model

The absorbed optical power is modelled as

$$P_{\text{abs}} = \eta_{\text{abs}} P_t [1 - H(\lambda, T)], \quad (9)$$

where η_{abs} is the optical absorption coefficient.

The thermal dynamics of the photonic device are represented by

$$C_{th} \frac{dT}{dt} = P_{\text{abs}} - \frac{T - T_a}{R_{th}}, \quad (10)$$

where C_{th} is the equivalent thermal capacitance, T_a is the ambient temperature, and R_{th} is the thermal resistance.

Substituting Equations (9) into (10) gives

$$C_{th} \frac{dT}{dt} = \eta_{abs} P_t [1 - H(\lambda, T)] - \frac{T - T_a}{R_{th}} \quad (11)$$

which establishes the proposed thermo-optical feedback loop:

$$T \rightarrow n_{eff} \rightarrow \lambda_r \rightarrow H \rightarrow P_{abs} \rightarrow T. \quad (12)$$

Adaptive Wavelength Stabilization

The instantaneous wavelength error is defined as

$$e_\lambda(k) = \lambda_{ref} - \lambda_r(k), \quad (13)$$

where λ_{ref} is the desired operating wavelength.

The adaptive compensation term is updated according to

$$\Delta\lambda_c(k+1) = \Delta\lambda_c(k) + \mu_\lambda e_\lambda(k), \quad (14)$$

where μ_λ is the adaptive wavelength-correction coefficient.

The corrected wavelength is consequently.

$$\lambda_c(k) = \lambda_{ref} + \Delta\lambda_c(k) \quad (15)$$

and the stabilized wavelength error becomes

$$e_{\lambda,c}(k) = \lambda_{ref} - \lambda_c(k). \quad (16)$$

The adaptive mechanism therefore continuously compensates for temperature-induced resonance displacement.

Unified Optimization Function

To jointly minimize thermal and optical degradation, the following normalized objective function is proposed:

$$J = w_1 e_\lambda^2 + w_2 P_{loss} + w_3 P_{abs} + w_4 (T - T_a)^2 + w_5 BER \quad (17)$$

where $w_1, \dots, w_5$ are weighting coefficients and BER represents bit-error rate.

The optimization problem is formulated as

$$J^* = \min_{\lambda_c, P_t, T} J \quad (18)$$

subject to

$$|e_\lambda| \leq e_{\lambda,max}, \quad (19)$$

$$T \leq T_{max}, \quad (20)$$

and

$$P_r \geq P_{min}. \quad (21)$$

These constraints ensure that the stabilization process maintains acceptable wavelength accuracy, temperature, and received optical power.

Thermal Stability Analysis

At steady state,

$$\frac{dT}{dt} = 0, \quad (22)$$

and from Equation (11),

$$T = T_a + R_{th}P_{abs}(T). \quad (23)$$

For a small temperature perturbation ΔT , local thermal stability requires

$$\boxed{R_{th} \frac{\partial P_{abs}}{\partial T} < 1.} \quad (24)$$

Using Equation (9),

$$\frac{\partial P_{abs}}{\partial T} = -\eta_{abs}P_t \frac{\partial H}{\partial T}. \quad (25)$$

Therefore, the stability condition becomes

$$\boxed{-R_{th}\eta_{abs}P_t \frac{\partial H}{\partial T} < 1.} \quad (26)$$

Equation (26) provides a direct analytical criterion for identifying stable thermo-optical operating conditions.

Expected Performance Evaluation

The proposed TORT framework can be evaluated by varying the ambient temperature, optical input power, thermal resistance, thermo-optic coefficient, and wavelength-channel spacing. The principal performance indicators include the resonance-wavelength deviation, received optical power, optical loss, temperature rise, stabilization time, and BER. A comparison between uncontrolled and adaptive wavelength operation can be performed using

$$\eta_\lambda = \left(1 - \frac{|e_{\lambda,c}|}{|e_{\lambda,u}|}\right) \times 100, \quad (27)$$

where $e_{\lambda,u}$ and $e_{\lambda,c}$ represent the uncontrolled and corrected wavelength errors, respectively. Similarly, the relative thermal improvement can be quantified using

$$\eta_T = \left(1 - \frac{\Delta T_c}{\Delta T_u}\right) \times 100. \quad (28)$$

These metrics provide quantitative measures of wavelength stabilization and thermal regulation.

DISCUSSION

The mathematical formulation demonstrates that the wavelength drift in an integrated photonic device is not solely an optical phenomenon but results from coupled optical and thermal interactions. The proposed Thermo-Optical Resonance Tracking (TORT) framework establishes a unified mathematical relationship between thermal variation, optical resonance, transmission characteristics, absorbed power, and adaptive wavelength stabilization in silicon-photonics communication devices. The fundamental resonance condition is defined by $m\lambda_r = n_{\text{eff}}(T)L(T)$ in Equation (1), where m is the resonance order, λ_r is the resonant wavelength, n_{eff} is the effective refractive index, and L is the optical path length; the temperature dependence of the refractive index is represented by $n_{\text{eff}}(T) = n_0 + \frac{dn_{\text{eff}}}{dT}(T - T_0)$ in Equation (2), where n_0 is the reference effective refractive index, dn_{eff}/dT is the thermo-optic coefficient, T is the device temperature, and T_0 is the reference temperature, while the temperature-dependent optical path is given by $L(T) = L_0[1 + \alpha_L(T - T_0)]$ in Equation (3), where L_0 denotes the reference path length and α_L is the thermal-expansion coefficient. Differentiating the resonance relationship produces $\frac{d\lambda_r}{dT} = \lambda_r \left[\frac{1}{n_{\text{eff}}} \frac{dn_{\text{eff}}}{dT} + \alpha_L \right]$ in Equation (4), which quantifies the wavelength sensitivity to temperature. The optical phase is subsequently defined as $\phi(\lambda, T) = \frac{2\pi n_{\text{eff}}(T)L(T)}{\lambda}$ in Equation (5), where λ is the operating optical wavelength, and the normalized transmission function $H(\lambda, T)$ in Equation (6) describes the temperature-dependent resonance transmission, with a representing the round-trip amplitude factor and δ representing the effective coupling/loss parameter. Temperature-dependent optical attenuation is modeled as $\alpha_{\text{opt}}(T) = \alpha_0 +$

$\alpha_T(T - T_0)$ in Equation (7), where α_0 is the reference attenuation and α_T is its temperature coefficient, allowing the received optical power to be calculated using $P_r = P_t e^{-\alpha_{opt}(T)L} H(\lambda, T)$ in Equation (8), where P_t and P_r are transmitted and received optical powers, respectively. The absorbed optical power is represented by $P_{abs} = \eta_{abs} P_t [1 - H(\lambda, T)]$ in Equation (9), where η_{abs} is the absorption coefficient, and the thermal dynamics are governed by $C_{th} \frac{dT}{dt} = P_{abs} - \frac{T - T_a}{R_{th}}$ in Equation (10), where C_{th} is thermal capacitance, T_a is ambient temperature, and R_{th} is thermal resistance; substitution produces the coupled thermo-optical equation $C_{th} \frac{dT}{dt} = \eta_{abs} P_t [1 - H(\lambda, T)] - \frac{T - T_a}{R_{th}}$ in Equation (11), thereby establishing the feedback sequence $T \rightarrow n_{eff} \rightarrow \lambda_r \rightarrow H \rightarrow P_{abs} \rightarrow T$ in Equation (12). To compensate for temperature-induced resonance displacement, the wavelength error is defined as $e_\lambda(k) = \lambda_{ref} - \lambda_r(k)$ in Equation (13), where λ_{ref} is the desired reference wavelength and k is the discrete control iteration, while the adaptive correction is updated using $\Delta\lambda_c(k+1) = \Delta\lambda_c(k) + \mu_\lambda e_\lambda(k)$ in Equation (14), where μ_λ is the adaptive correction coefficient; consequently, the corrected wavelength is $\lambda_c(k) = \lambda_{ref} + \Delta\lambda_c(k)$ in Equation (15), and the corrected error is $e_{\lambda,c}(k) = \lambda_{ref} - \lambda_c(k)$ in Equation (16). The overall stabilization objective is formulated as $J = w_1 e_\lambda^2 + w_2 P_{loss} + w_3 P_{abs} + w_4 (T - T_a)^2 + w_5 BER$ in Equation (17), where J is the composite performance index, $w_1, \dots, w_5$ are weighting coefficients, P_{loss} is optical/electrical loss, and BER is bit-error rate; the optimum operating condition is obtained from $J^* = \min_{\lambda_c, P_t, T} J$ in Equation (18) subject to the wavelength-error constraint $|e_\lambda| \leq e_{\lambda,max}$ in Equation (19), the maximum temperature constraint $T \leq T_{max}$ in Equation (20), and the minimum received-power requirement $P_r \geq P_{min}$ in Equation (21). At thermal equilibrium, $dT/dt = 0$ in Equation (22), yielding $T = T_a + R_{th} P_{abs}(T)$ in Equation (23), which directly relates steady-state temperature to absorbed power. The local thermal stability requirement is then expressed as $R_{th} \frac{\partial P_{abs}}{\partial T} < 1$ in Equation (24), ensuring that a small temperature perturbation does not generate an uncontrolled increase in absorbed power; using the absorbed-power relationship gives $\frac{\partial P_{abs}}{\partial T} = -\eta_{abs} P_t \frac{\partial H}{\partial T}$ in Equation (25) and consequently the stability condition $-R_{th} \eta_{abs} P_t \frac{\partial H}{\partial T} < 1$ in Equation (26). Finally, wavelength-stabilization improvement is quantified through $\eta_\lambda = \left(1 - \frac{|e_{\lambda,c}|}{|e_{\lambda,u}|}\right) \times 100$ in Equation (27), where $e_{\lambda,u}$ is the uncontrolled wavelength error, while thermal improvement is represented by $\eta_T = \left(1 - \frac{\Delta T_c}{\Delta T_u}\right) \times 100$ in Equation (28), where ΔT_c and ΔT_u denote corrected and uncontrolled temperature rises, respectively. Collectively, Equations (1)–(28) form the complete TORT mathematical framework, in which temperature modifies refractive index and optical dimensions; these changes shift resonance and transmission; transmission determines absorbed power, absorbed power modifies temperature, and the adaptive controller compensates for the resulting wavelength drift, thereby providing a unified analytical basis for thermally stable and wavelength-accurate silicon-photonics optical communication systems. According to Equation (4), temperature changes modify the resonant wavelength through both refractive-index variation and thermal expansion. Equation (8) further indicates that resonance displacement directly affects received optical power. Because the absorbed power in Equation (9) depends on the transmission function, optical detuning can subsequently modify device heating. This establishes the closed feedback mechanism represented by (12). The adaptive correction mechanism in Equation (14) introduces a dynamic response to this disturbance rather than relying exclusively on passive thermal stabilization. The objective function in (17) further allows wavelength accuracy, thermal behavior, optical loss, and communication quality to be considered simultaneously. The stability criterion in Equation (24) provides additional analytical condition for avoiding excessive positive thermo-optical feedback.

CONCLUSION

This study proposed a thermo-optical resonance tracking (TORT) mathematical framework for wavelength stabilization in silicon photonic optical communication systems. The proposed model integrates the temperature-dependent refractive index, thermal expansion, resonant wavelength

displacement, optical transmission, temperature-dependent attenuation, absorbed optical power, and thermal dynamics into a unified formulation. An adaptive wavelength-correction mechanism was developed to compensate for temperature-induced resonance drift, while a multi-objective optimization function incorporated wavelength error, optical loss, absorbed power, temperature deviation, and BER. A local thermal stability condition was additionally derived to identify stable operating regions. The resulting framework provides a mathematical basis for analyzing thermo-optical interactions in microring resonators, resonant modulators, WDM filters, and integrated photonic transceivers. Future work can extend the model toward experimental silicon-photonics platforms, multi-channel WDM systems, nonlinear thermal effects, machine-learning-assisted wavelength prediction, and hardware-in-the-loop validation.

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