CLAP: a Crosstalk and Loss Analysis Platform for Optical Interconnects

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***Abstract*—Basic photonic devices in inter- and intra-chip optical networks suffer from inevitable power loss and crosstalk noise. Incoherent crosstalk introduces quick power fluctuations, while coherent crosstalk varies the optical power of the optical signal in optical interconnection networks (OINs). As a result, the accumulative crosstalk in large scale OINs considerably hurts the signal-to-noise ratio (SNR) and imposes high power penalties. In this work, we aim at studying the worst-case incoherent and coherent crosstalk in OINs at the system level. The proposed analytical models are integrated into a newly developed crosstalk and loss analysis platform, called CLAP, to facilitate the SNR analyses in arbitrary OINs.**

As the technology advances and allows the integration of a large number of processing cores on a single die, metallic interconnects cannot efficiently address the on-chip communication requirements in multiprocessor systems-on-chip (MPSoCs) due to their high power dissipation, high latency, and low bandwidth. Optical interconnects using wavelength-dimension multiplexing (WDM), on the other hand, can bring ultra-high bandwidth and very low power consumption as well as low latency to the on-chip communication in MPSoCs. However, the imperfect structure of photonic devices in optical interconnection networks (OINs) causes inevitable crosstalk noise and power loss in such devices. The crosstalk noise and power loss are very small at the device level, but can accumulate in large scale OINs and cause performance degradation.

The crosstalk in OINs can be classified as *intrachannel* and *interchannel* crosstalk. Intrachannel crosstalk is when the crosstalk signal is at the same wavelength as that of the desired optical signal. In contrast, interchannel crosstalk is when the crosstalk signal is at a wavelength sufficiently different from the desired signal's wavelength. The intrachannel crosstalk noise is of critical concern because it cannot be removed by filtering, and hence we target to study this type of crosstalk noise in OINs. The intrachannel crosstalk noise can be either incoherent, whose phase is uncorrelated with the desired optical signal, or coherent, whose phase is correlated with the desired optical signal. The incoherent crosstalk noise may also be a coherent combination of crosstalk contributors and then cause much higher noise power [1]. When the optical propagation delay differences exceed the coherent time of the laser, then the crosstalk noise contributors are incoherent with the desired optical signal and, in the worst-case, their powers can be accumulated and ultimately hurt the SNR at the receiver. On the other hand, when the propagation delay differences are smaller than the coherent time of the laser, then the crosstalk contributors will combine coherently to form a composite crosstalk. The coherent crosstalk causes power fluctuations when the optical propagation delays' differences are much less than the time duration of one bit, as shown in [1]. In the same work, it was proved that the coherent crosstalk also causes noise if the mentioned condition is not satisfied.

This work is partially supported by GRF620911, GRF620512, and DAG11EG05S.

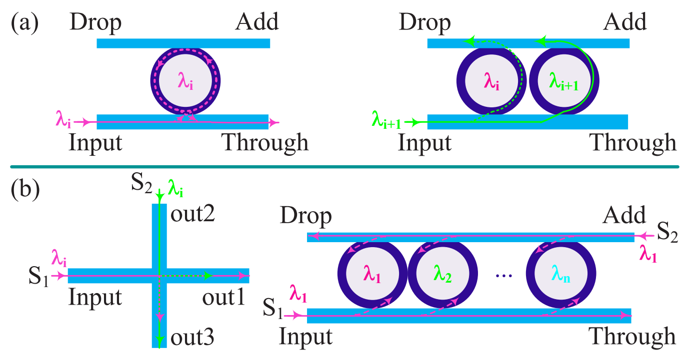

Fig. 1. Crosstalk and power loss in basic optical devices: (a) coherent crosstalk and (b) incoherent crosstalk.

The major contribution of this work is to extend the newly developed crosstalk and loss analysis platform (CLAP) to include the coherent crosstalk analysis in arbitrary OINs [2]. Relying on our previous works [2] and [3], we present a formal analytical approach that enables worst-case incoherent and coherent crosstalk analyses in different OIN architectures. The presented hierarchical formal analytical approach models the power loss and crosstalk in basic photonic devices and utilizes those analyses to study the worst-case crosstalk and SNR at the router and network levels in OINs. Fig. 1 indicates the incoherent and coherent crosstalk in a waveguide crossing and parallel switching element (PSE) as an example. Considering Fig. 1a, a portion of the optical signal, which has experienced a different delay compared with the desired optical signal, adds to the desired optical signal as coherent crosstalk. As can be seen from Fig. 1b, when the optical signals S_1 and S_2, which are from different power sources but have the same wavelength, pass a common waveguide crossing or PSE, a portion of the optical signal S_1 (S_2) mixes with the optical signal S_2 (S_1) as incoherent crosstalk noise. Also, power loss will be imposed on an optical signal when it passes a waveguide crossing or microresonator (MR) as well as when it couples into an MR.

With regard to the basic photonic device characteristics, we

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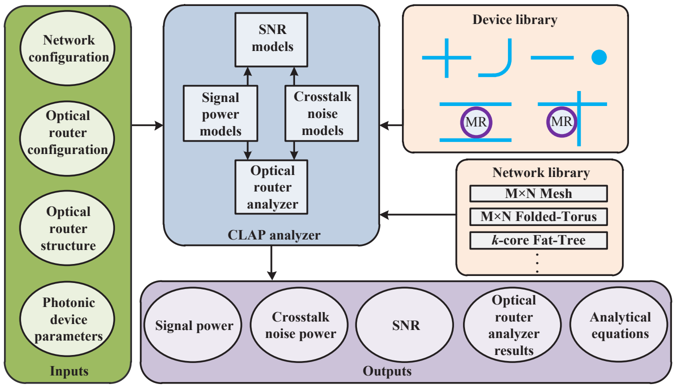

Fig. 2. CLAP's overview.

develop an analytical approach to analyse the power loss and incoherent and coherent crosstalk in such devices. Considering the PSE shown in Fig. 1, (1) indicates the signal power on the Through port after it passes the MRs, and (2) calculates the signal power on the Drop port by considering the drop loss in the MR.

$$P_T^{\lambda_i} = L_p^n P_{in}^{\lambda_i} \quad (1)$$

$$P_D^{\lambda_i} = L_p^{i-1} L_d P_{in}^{\lambda_i} \quad (2)$$

In these equations, L_p and L_d are the passing loss and drop loss of the MR, respectively. Also, λ_i indicates the optical wavelength under consideration, and n indicates the total number of wavelengths in the OIN. P_{in} is the optical signal power at the input port. Considering the coherent crosstalk in the PSE shown in Fig. 1a, we consider the worst-case scenario, in which the crosstalk signal and the desired optical signal are out of phase and when the state of polarization (SOP) of the crosstalk signal is the same as the SOP of the desired optical signal. As a result, the coherent crosstalk diminishes the desired optical signal power at the receiver, given that the optical propagation delays' differences are within the time duration of one bit. The introduced power losses to the desired optical signal can be calculated based on the received signal power and the total coherent crosstalk power at the receiver [4]. The coherent crosstalk power in the PSEs shown in Fig. 1a can be analyzed using (5) and considering the passing loss calculation in (1). According to Fig. 1b, the power loss imposed on the optical signal while passing a waveguide crossing is calculated in (3), while (4) calculates the incoherent crosstalk noise at the other two output ports.

$$P_{out1}^{\lambda_i} = L_c P_{in}^{\lambda_i} \quad (3)$$

$$P_{out2}^{\lambda_i} = P_{out3}^{\lambda_i} = X_c P_{in}^{\lambda_i} \quad (4)$$

In these equations, L_c is the crossing loss in a waveguide crossing and X_c is the crosstalk coefficient defined for the waveguide crossing. The incoherent crosstalk noise in the PSE shown in Fig. 1b can be calculated based on the Lorentzian power transfer function of the MR. For the optical signal carried on the wavelength λ_i, the optical power that is transferred to the drop port can be expressed as (5) [5].

$$\frac{P_{drop}^{\lambda_i}}{P_{in}^{\lambda_i}} = \frac{\delta^2}{(\lambda_i - \lambda_{MRm})^2 + \delta^2} \quad (5)$$

In this equation, 2δ is the 3 dB bandwidth of the MR and it can be calculated based on $Q = \frac{\lambda_{MR}}{2\delta}$, in which Q is the quality factor of the MR. λ_{MRm} is the resonant wavelength of the *m-th* MR.

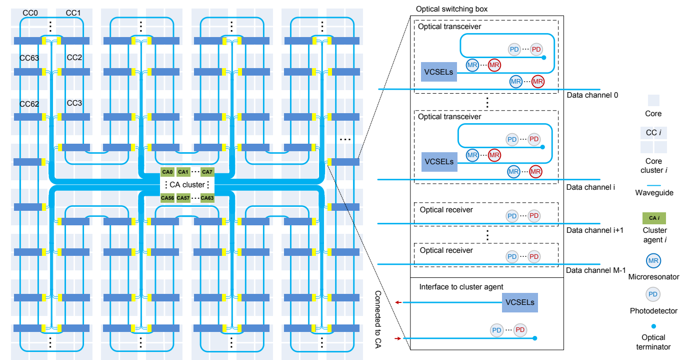

Fig. 3. The sectioned undirectional optical ring (SUOR) structure [7].

The analytical models at the basic device level can be used to study the power loss, crosstalk noise, and SNR at the optical router and network levels. The newly developed CLAP is extended to realize the coherent crosstalk analysis in arbitrary OINs. Fig. 2 illustrates the internal structure of CLAP. CLAP is publicly released and it is available online with documentation [2], [6]. CLAP has a complete library of basic photonic devices, which allows the design of different optical router and network architectures. Using different considered input files, the user can easily define the optical router structure and configuration, the optical network and its communication pattern, the loss and crosstalk noise values in the basic devices as well as their dimensions, the FSR, the MR's Q-factor, the number of wavelengths in the network, the laser input power, etc. CLAP analyses the power loss, incoherent and coherent crosstalk noise, and SNR at the destination of an optical link that the user has defined. Furthermore, CLAP is capable of providing the worst-case and the average results. By way of example, we employed CLAP to compare the worst-case SNR and power loss in two ring-based optical networks-on-chip (ONoCs), Corona and sectioned undirectional optical ring (SUOR) networks, both of which consisted of 256 processor cores [3], [7]. Fig. 3 indicates the architectural overview of SUOR. The analyses results indicate that the crosstalk and power loss from the basic optical devices considerably hurt the SNR, and especially impose severe power loss in the ring-based ONoCs: for example, the worst-case SNR and power loss on the Corona's data channel are equal to 13 dB and -69 dB, respectively.

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