Thermal Modeling of Small Form Factor

Pluggable Devices: Different Approaches

Most of the industrial Routers and Switches today use optical transceivers for transmitting and receiving data over fiber-optic cables. There are many types of these Opto-electronic packages such as Xenpaks, X2s, XFP's , SFP , SFP+. One widely used optical transceiver is the SFP – Small form factor Pluggable Device (Figure 1) for which different thermal modeling techniques will be discussed and reviewed.

Figure 1. SFP Module [1]

A typical transceiver's generic layout is shown in Figure 2.

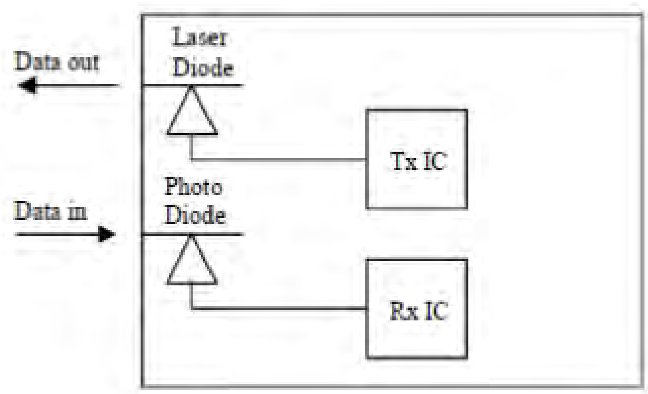

Figure 2. A General Schematic Diagram of a Transceiver [2]

The internal construction of an SFP module is shown in Figure 3.

Figure 3. A SFP Module with the Outer Housing Removed to Show the Internal Construction [3]

A typical SFP module consists of a Transmitter Optical Sub Assembly (TOSA), Receiver Optical Sub Assembly (ROSA), associated IC's, circuitry, PCB and housing. The SFP optical transceivers have lasers for transmitting the data. The performance and longevity of the laser depends on the ambient (local) temperature it operates in and the thermal characteristics of the packaging of these devices, amongst other factors. Therefore it is imperative to accurately account for the SFP modules in a system during thermal analysis.

Ideally it is best to model the SFP in detail. Some vendors do provide thermal models of the SFP modules in commercially available CFD packages such as Flotherm or Icepak. However, due to its small footprint and the fact that, generally a number of SFP modules are designed into a router or switch, using these thermal models into the system becomes computationally prohibitive.

Raghupathy and Shen [2] have compared different approaches to modeling a SFP module in a system and have analyzed the merits and de-merits of each approach. This article will briefly examine the different approaches and review the findings of their study.

The four modeling methods studied and presented for comparison were:
1) Detailed Model
2) Lumped Model
3) Two-Resistor Network Model
4) DELPHI Based Multi-Resistor Network Model

In the detailed model [1] the SFP module had as much detail as possible. The model was constructed based on natural convection experimental setup and was done in two stages. The details of the thermal modeling of the SFP and the experimental set up to validate and generate a boundary condition independent compact thermal model can be obtained from Raghupathy et al. [4]. The results obtained from this approach were used to compare with the results obtained from the other three modeling approaches. While the detailed model did yield a grid independent solution at about 600,000 computational cells, using this approach in a system level thermal model with multiple SFP modules renders the solution of the thermal model impossible to solve.

A widely used industry practice by thermal engineers is to model the SFP's as a cuboid with a fixed (lumped) thermal conductivity. The entire cuboid is assumed to dissipate the power generated by the different power dissipating components inside the SFP. While the thermal conductivity value used varies between engineers, this is still not an entirely wrong approach since the SFP housing has a fairly high conductivity and in general, a large thermal gradient on the surface of the housing is rarely seen. However the downside of using this approach is that it still requires a significant amount of computational cells to resolve the case temperature. In systems with multiple SFP's, this impacts the overall mesh count of the system. For this study the researchers used a k value of 114 W/m-K, that of Zamac alloy.

In the two-resistor model, the authors have used the model developed by Shen et.al [5]. The two-resistor model addresses the issue of mesh count and thereby computational resources since it requires only 2 cells for resolving the heat transfer within the SFP module but is dependent on the airflow and the board conductivity. The researchers, in this approach, incorporated different flow velocities (forced convection) and the results were compared against the detailed and DELPHI-based network models.

The DELPHI-based multi-resistor networked model, developed earlier by Raghupathy et al [4,6] was used in this study as well. This approach captures fairly accurately the heat flows and temperatures within the SFP module using 9 grid cells.

The four models were compared with the following boundary conditions:

1) Natural convection with and without heat sinks
2) Forced convection at different airflow velocities (100, 200 and 400 m/s)

For the natural convection case study a single SFP without the EMI cage was placed vertically inside a duct. See Figure 4.

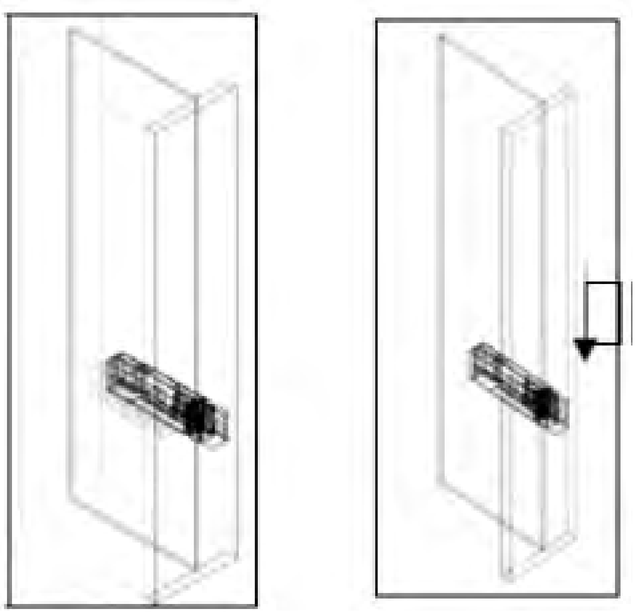

Figure 4. Flotherm Model of an SFP Module With and Without the Heat Sinks in a Natural Convection Setup [2]

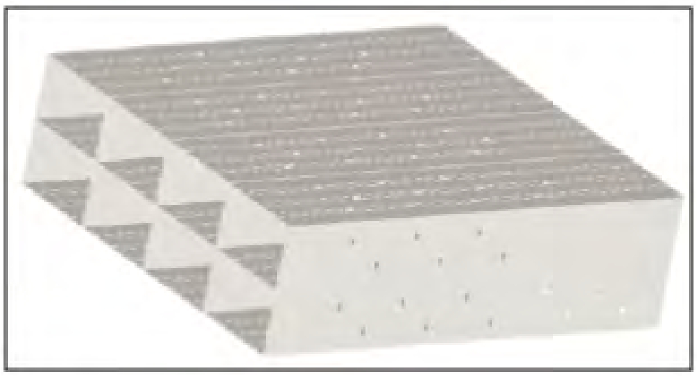

Figure 5. A 2X4 EMI Cage That Was Used in the Flotherm Models for the Forced Convection Setup [2]

For the forced convection studies, eight SFP modules were placed in a 2X4 EMI cage as shown in Figure 5. The cage was modeled in detail and the SFP modules were offset 0.3mm from the EMI cage along the length. The numbering of the SFP's are as shown in Figure 6 and the simulations were carried out at 100, 200, 400 m/s in a 20°C ambient.

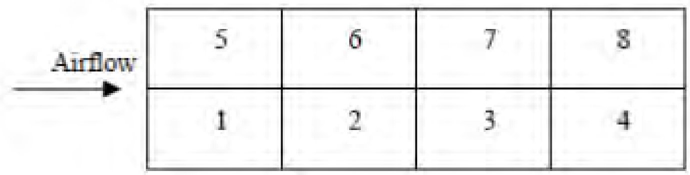

Figure 6. The Numbering Convention Used for the SFP's for the Forced Convection Setup

In order to ensure that the environment does not change between the models they were all built into the same system level Flotherm model. [2]

The results from the natural convection studies are shown in Tables 1 and 2. For both these cases, for the two-resistor method values of $R_{j\text{-}c}$ = 0.1°C/W and $R_{j\text{-}b}$ = 50°C/W were used. For the case with the heat sink a typical heat sink that is used for SFP packages were used in the thermal model.

	Detailed	Two-Resistor	Lumped	DELPHI
T_c	29.3	27.5	28.7	29.2
T_c-T_a	9.3	7.5	8.7	9.2
Error		19.4%	6.5%	1.6%

Table 1. Comparison of SFP Temperatures, Temperature Rise Above Ambient and % Error, without Heat Sink in Natural Convection

	Detailed	Two-Resistor	Lumped	DELPHI
T_c	28.5	26.2	28.1	28.2
T_c-T_a	8.5	6.2	8.1	8.2
Error		27.1%	4.7%	3.5%

Table 2. Comparison of SFP Temperatures, Temperature Rise Above Ambient and % Error, with Heat Sink in Natural Convection

In the case of Natural convection, with or without heat sink, the % error with the DELPHI model is the least in both cases. However the lumped model also predicted case temperatures within a reasonable margin of 7%. The results suggest that for a first level analysis the lumped thermal conductivity model can predict temperatures within 10% error which is a fairly good starting point. For detailed analysis it is best to go to a DELPHI model.

Air Flow (m/s)	$R_{j\text{-}c}$ (°C/W)	$R_{j\text{-}b}$ (°C/W)
100	59.2	9.77
200	52.92	9.95
400	46	10

Table 3. The Junction to Case and Junction to Board Resistance Used for the Forced Convection Cases Considered [5]

		Detailed	Two-Resistor	Lumped	DELPHI
SFP1	T_c	29.7	30.1	29.4	30.3
	T_c-T_a	9.7	10.1	9.4	10.3
	Error		-4.5%	2.8%	-5.7%
SFP2	T_c	31.3	31.8	31	31.9
	T_c-T_a	11.3	11.8	11	11.9
	Error		-4.6%	2.5%	-5.3%
SFP3	T_c	31.8	32.4	31.5	32.4
	T_c-T_a	11.8	12.4	11.5	12.4
	Error		-4.8%	2.4%	-5.1%
SFP4	T_c	31.2	31.8	31	31.8
	T_c-T_a	11.2	11.8	11	11.8
	Error		-5.8%	1.4%	-5.4%
SFP5	T_c	28.8	28.8	28.6	29.1
	T_c-T_a	8.8	8.8	8.6	9.1
	Error		-0.2%	2.5%	-3.4%
SFP6	T_c	30.4	30.8	30.2	20.7
	T_c-T_a	10.4	10.8	10.2	10.7
	Error		-3.8%	2.0%	-2.9%
SFP7	T_c	30.9	31.5	30.7	31.3
	T_c-T_a	10.9	11.5	10.7	11.3
	Error		-5.2%	1.7%	-3.7%
SFP8	T_c	30.6	31.2	30.4	30.9
	T_c-T_a	10.6	11.2	10.4	10.9
	Error		-6.1%	1.6%	-2.8%

Table 4. Comparison of SFP Temperatures, Temperature Rise Above Ambient and Error, for Forced Convection of 1 m/s

For the forced convection simulations, the values for $R_{j\text{-}c}$ and $R_{j\text{-}b}$ for the different air velocities are shown in table 3. The reasoning behind usage of these values can be found in Shen [5].

Table 4 shows the SFP temperatures, modeled within the EMI cage, when the inlet airflow is set to be a uniform 1 m/s. It is seen that the lumped model does predict temperatures within 5% error. But for larger models the downside will be the number of cells required to adequately represent each of the SFP, thereby significantly increasing the overall grid count of the system level thermal model. The DELPHI model still seems to be a viable option with error within 4% and as stated earlier each SFP requires only 9 nodes. The Two resistor model, although has the maximum error compared to the other two approaches, still does predict temperatures within 95% accuracy.

		Detailed	Two-Resistor	Lumped	DELPHI
SFP1	T_c	32.8	33.1	32.4	32.8
	T_c-T_a	12.8	13.1	12.4	12.8
	Error		-2.6%	2.8%	0.0%
SFP2	T_c	34.3	34.7	33.9	34.2
	T_c-T_a	14.3	14.7	13.9	14.2
	Error		-2.6%	3.1%	0.7%
SFP3	T_c	34.7	35.2	34.3	34.6
	T_c-T_a	14.7	15.2	14.3	14.6
	Error		-3.1%	2.7%	0.7%
SFP4	T_c	34.2	34.6	33.8	34.1
	T_c-T_a	14.2	14.6	13.8	14.1
	Error		-2.8%	2.7%	0.7%
SFP5	T_c	32.2	32.6	31.8	31.9
	T_c-T_a	12.2	12.6	11.8	11.9
	Error		-2.9%	2.9%	2.5%
SFP6	T_c	33.7	34.3	33.3	33.3
	T_c-T_a	13.7	14.3	13.3	13.3
	Error		-4.3%	2.7%	2.9%
SFP7	T_c	34.2	34.8	33.8	33.7
	T_c-T_a	14.2	14.8	13.8	13.7
	Error		-4.5%	2.9%	3.5%
SFP8	T_c	33.8	34.5	33.5	33.4
	T_c-T_a	13.8	14.5	13.5	13.4
	Error		-5.2%	2.5%	2.9%

Table 5. Comparison of SFP Temperatures, Temperature Rise Above Ambient and Error, for Forced Convection of 2 m/s

		Detailed	Two-Resistor	Lumped	DELPHI
SFP1	T_c	27.1	27.4	26.9	27.6
	T_c-T_a	7.1	7.4	6.9	7.6
	Error		-4.2%	2.9%	-7.0
SFP2	T_c	29.2	29.5	28.8	29.7
	T_c-T_a	9.2	9.5	8.8	9.7
	Error		-3.3%	4.4%	-5.4%
SFP3	T_c	29.9	30.5	29.5	30.4
	T_c-T_a	9.9	10.5	9.5	10.4
	Error		-6.1%	4.2%	-5.1%
SFP4	T_c	29.6	30.1	29.1	29.9
	T_c-T_a	9.6	10.1	9.1	9.9
	Error		-5.2%	5.1%	-3.1%
SFP5	T_c	26.2	25.8	26	26.4
	T_c-T_a	6.2	5.8	6	6.4
	Error		-6.5%	3.9%	-3.2%
SFP6	T_c	28.1	28.3	27.8	28.4
	T_c-T_a	8.1	8.3	7.8	8.4
	Error		-2.5%	3.4	-3.7%
SFP7	T_c	28.9	29.2	28.5	29
	T_c-T_a	8.9	9.2	8.5	9
	Error		-3.4%	4.4%	-1.1%
SFP8	T_c	28.7	29.1	28.3	28.8
	T_c-T_a	8.7	9.1	8.3	8.8
	Error		-4.6%	4.6%	-1.1%

Table 6. Comparison of SFP Temperatures, Temperature Rise Above Ambient and Error, for Forced Convection of 4 m/s

Table 5 shows the SFP temperatures, modeled within the EMI cage, when the inlet airflow is set to be uniform at 2 m/s. Here again the lumped model predicts temperatures within 97% accuracy while the error with the DELPHI model is slightly higher than before. The two-resistor model is fairly reliable with error less than 5%.

Table 6 shows the SFP temperatures, modeled within the EMI cage, when the inlet airflow is set to be uniform at 4 m/s. Here again the lumped model is slightly better than the two-resistor model but all of them have less than 10% error. What is interesting with the DELPHI model, at higher airflow, it seems to consistently predict temperatures which is slightly above the expected temperature (i.e Detailed model) and makes this modeling approach a conservative one. More discussion on why the DELPHI model has higher error can be found in [2].

We have seen based on the work carried out by Raghupathy et. Al [2] that for a first level thermal analysis using a lumped thermal conductivity of 117 W/m-k for the SFP module, modeled as a cuboid will predict temperatures within 90% accuracy. However the down side with this approach is that this could add significantly to the mesh count of the system. The other alternative is the two resistor model, but it is necessary to have an idea of the air flow speed around the SFP since the resistance values are highly dependent on the air flow regime.

The DELPHI model, while it does overcome the boundary condition dependency of the two-resistor model, the accuracy level is slightly compromised. Additionally the DELPHI model is not package independent. A DELPHI model has to be generated for each specific SFP or an optical package.

In conclusion, for a preliminary first-order analysis, use the lumped model. If the flow regime is known then the two-resistor model is helpful for iterative analyses because of the low mesh count contribution from SFP modules. When flow regime is unknown, and the number of SFP's in the system is very high and using cuboids for each SFP is computationally prohibitive, then a DELPHI model can be an effective approach for obtaining reasonable thermal data.

References:

1. www.startech.com

2. Raghupathy, A.P., and Shen, J., "Thermal Analysis of Opto-Electronic Packages – the DELPHI- Based Compact Thermal Model and Other Modeling Practices in the Industry." 26th IEEE SEMI-THERM Symposium 2009.

3. www.dz863.com

4. Raghupathy, A.P., Aranyosi, A., Ghia, U., Ghia, K., and Maltz, W., "Development of Boundary-Condition Independent Compact Thermal Models for Opto-Electronic Packages." ASME Interpack, IPACK 2009-89092, San Francisco, CA, July 2009.

5. Shen, J., and Raghupathy, A.P., "A Simplified CFD Modeling Technique for Small Form Factor Pluggable Transceiver." Proc. SEMITHERM 2010, San Jose, CA, Feb 21-25, 2010.

6. Raghupathy, A.P., Aranyosi, A., Ghia, U., Ghia, K., and Maltz, W., "Validation Studies of a DELPHI-type Boundary-Condition-Independent Compact Thermal Model for an Opto-Electronic Package with Multiple Heat Sources." Proc. THERMINIC 2009, Leuven, Belgium, Oct 7-9, 2009.