# Analysis of Hybrid-Integrated High-Speed Electro-Absorption Modulated Lasers Based on EM/Circuit Co-simulation

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# Analysis of Hybrid-Integrated High-Speed Electro-Absorption Modulated Lasers Based on EM/Circuit Co-simulation

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*Abstract* — **An improved electromagnetic simulation (EM) based approach has been developed for optimization of the electrical to optical (E/O) transmission properties of integrated electro-absorption modulated lasers (EMLs) aiming at 100 Gbit/s Ethernet applications. Our approach allows for an accurate analysis of the EML performance in a hybrid microstrip assembly. The established EM-based approach provides a design methodology for the future hybrid integration of the EML with its driving electronics.**

*Index Terms* — **EM-based design, EML, 100 Gbit/s Ethernet, Hybrid integration**

## I. Introduction

High speed multi-gigabit networks are essential for future large volume data transmission. 100 Gbit/s Ethernet is considered to be the next standard following the present 10 Gbit/s Ethernet standard [1]. The optoelectronic transceiver working at a full-rate of 100 Gbit/s is crucial for realizing cost efficient 100 Gbit/s Ethernet systems. The hybrid integration of the highest speed optoelectronic transducers with their driving electronics becomes very challenging when aiming at the rate of 100 Gbit/s and must be supported by extensive electromagnetic (EM) simulation based activities [2].

The electro-absorption modulator (EAM) based on InP is a widely used transmitter component in 40Gbit/s optical communication systems [3]. For the intended bit-rate of 100 Gbit/s the EAM offers several advantages such as large absorption variations at low driving voltages, very small size, and mature integration with a laser. Based on a single-active layer technology packaging costs can be reduced through the monolithic integration of an EAM with a laser on InP to form an electro-absorption modulated laser (EML) structure [4]. The electrical driver for the EML structure still has to be connected using a low parasitic flip-chip or wire-bonding approach. InP DHBT is the preferred device technology for 100 Gbit/s electronic drivers because of their high-speed and high-breakdown characteristics. The high breakdown is crucial to provide sufficient current drive to the EML. For 100 Gbit/s operation an electrical to optical transmission bandwidth >70 GHz is desired, which is not easy to achieve with the hybrid integration scheme. The electrical to optical transmission bandwidth for the driver-EML integration scheme is approximately limited by the time-constant $C_s(Z_o \| Z_d+R_s)$ where $Z_d$ is the driver impedance, $Z_o$ the load impedance, $C_s$ the EAM junction capacitance, and $R_s$ the EAM series resistance [5]. Driver and load impedances less than 50Ω have been proposed as a means to overcome the inherent bandwidth limitation of the EAM under conventional driving [6].

It is the aim of this paper to describe the impact of the hybrid integration on the transmission properties of very high-speed EML structures using electromagnetic simulation. An improved EM simulator setup is proposed, which allows for a realistic determination of the electrical and optical properties of EML structures. The EM setup has been verified against electrical reflection measurements performed on an EML structure up to 65 GHz. For the first time, it is proposed to employ an EM/circuit co-simulation approach in the analysis of a monolithically integrated EML structure in a hybrid microstrip assembly with a record bandwidth exceeding 60GHz. The EM/circuit co-simulation approach has been successfully applied in order to explain the origin of a non-ideal wave-like behavior in the measured E/O transmission characteristic.

## II. EM simulation Setup

A model of the fabricated EML structure implemented into the 3D FEM based EM simulator, Ansoft HFSS, is shown in Fig. 1. The EAM part has a length of 50um and consists of a heterostructure AlGaInAs multi-quantum well (MQW) stack. The lumped EAM provides sufficiently low RC-parasitics and high extinction ratio for 100 Gbit/s Ethernet applications. Details in the fabrication process of the EML structure can be found in [7]. The shown EML structure is similar to the one used in the microstrip assembly. The only exception is the ground pillars which are not needed in the EML microstrip assembly. The bridge configuration in the HFSS setup resembles the coplanar excitation coming from the GSG probe employed in the on-wafer measurements. The setup presented here is utilized in order to verify the EM modeling capability for the monolithically integrated EML structure. Subsequently, this setup is used in accessing the overall module performance in the hybrid assembly using microstrip lines.

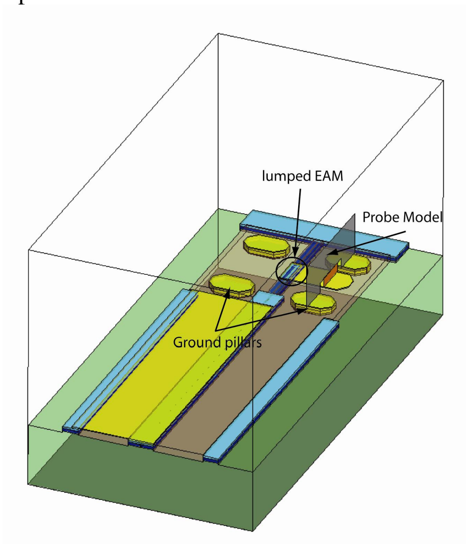


Fig. 1. HFSS model of fabricated EML structure used in on-wafer measurements. The probe GSG excitation is resembled using the bridge configuration shown.

It should be noticed that the impedance of the EAM diode junction depends on the optical power and applied signal swing in a nonlinear manner, and hence cannot be predicted by EM simulation. Instead a lumped small-signal equivalent circuit model for the MQW stack in the EAM and the laser junction parts are included into the HFSS EM simulation. This can be accomplished by using lumped RCL-boundary conditions available in the Ansoft HFSS simulator [8]. For the EAM junction typical values for the junction capacitance $C_s$ and dynamic photocurrent-resistance $R_{ph}$ are substituted into the HFSS simulation domain, while a single capacitor $C_{laser}$ is substituted for the laser MQW in a similar manner. In this way, it is possible to obtain a more realistic view of the optical and electrical properties of the full EML structure from the EM simulation.

As a verification of the HFSS simulation setup using lumped impedance boundaries for the MQW EAM diode junction, Fig. 2 compare the measured and simulated electrical reflection coefficient. A good agreement is obtained between the measured response and the HFSS simulation result obtained employing the setup shown in Fig. 1. It should be observed that both the amplitude and the phase are accurately captured in the EM simulations as compared to measurements up to 65 GHz. This verifies the EML intrinsic circuit model developed in [8]. Given this EML circuit model it is possible to investigate the EML embedding circuitry. This includes the wirebonded microstrip lines and load terminations, as detailed in the following section.

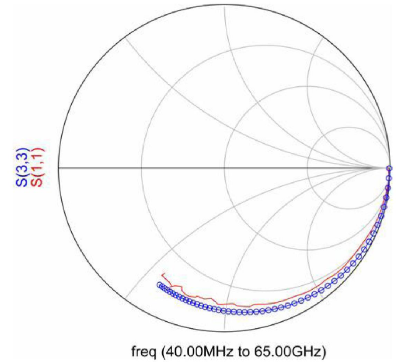


Fig. 2. Verification of HFSS setup for EML simulation using lumped element boundary conditions for MQW. Solid line: Measured electrical reflection; Symbols: HFSS simulation result.

## III. EML IN MICROSTRIP ASSEMBLY

The integrated EML structure has been wire-bonded onto 50Ω microstrip lines on an alumina ceramic substrate as shown in Fig. 3. The input ceramic includes a coplanar-to-microstrip transition for on-wafer probing, while the output ceramic is terminated in either standard 50Ω or with 35Ω resistive loads. The experimental results of the assembled EML structure demonstrate impressive 3dB bandwidth capabilities of approximately 45 GHz and 60 GHz for the microstrip assembly using 50Ω and 35Ω loads, respectively [7]. For the assembled EML structure shown in Fig. 3 a coplanar microwave signal is applied at the far left end. This microwave signal propagates down the microstrip line and modulates the optical power in the EAM MQW guide. The microwave signal is ideally absorbed by the loads at the far right end in order to avoid reflections. The efficiency of the modulation process at higher frequencies determines the 3dB bandwidth of the electrical to optical transmission response. In purely electrical terms it is the voltage developed across the EAM intrinsic junction which determines the E/O transmission response. This voltage, however, is not readily available from the EM simulation results. Therefore we propose to employ an EM/circuit co-simulation approach in the analysis of the structure shown in Figure. 3.

Turning now our attention towards the EM/circuit co-simulation of the microstrip assembly of the integrated EML structure we propose to perform simulations by parts. To allow for an efficient simulation of the full microstrip assembly the structure is subdivided into three parts as indicated in Figure. 3. The first part contains the coplanar-to-microstrip transition and the main part of the

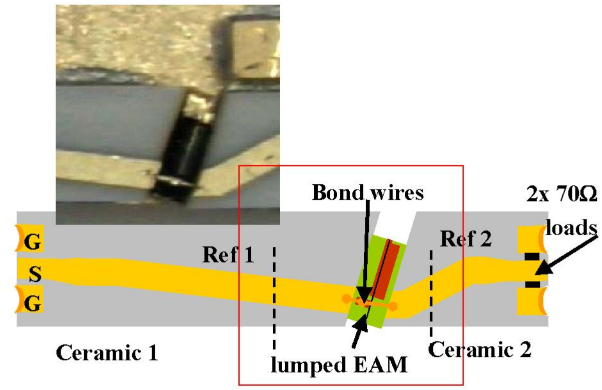


Fig. 3. Top-down view of microstrip assembly of EML structure. Insert shows photograph of wirebonded EML. Reference planes for simulation by parts are also shown.

input microstrip line (denoted ceramic 1). The second part, located between the reference planes (Ref1 and Ref2), contains the monolithically integrated EML structure including lumped impedance boundaries for the EAM diode junction wire-bonded onto the microstrip lines. Finally, the third part contains the load resistors connected by the output microstrip line (denoted ceramic 2). Wave-ports are employed at the reference planes (Ref1 and Ref2) while the GSG excitation at the input is obtained using our preferred bridge configuration. The total computational time for the three parts meshed at 65 GHz using 20 adaptive passed is 1h12m when performed on a 2.71 GHz AMD Athlon 64 bit CPU with 8GB of ram. The obtained HFSS simulation results are subsequently employed as S-parameter data blocks representing the input and output ceramics in the ADS microwave simulator environment. Thereby the propagation characteristics, including losses, dispersion and possible mode-conversion, experienced by the microwave signal can be accurately included into the EM/circuit co-simulation without resorting to complicated equivalent circuit modeling. Only the HFSS simulation results for the part containing the wire-bonded integrated EML structure needs to be represented with an equivalent circuit model. Fortunately the lumped equivalent circuit model for the monolithically integrated EML has already been developed in our previously work [8]. In order to fit the HFSS simulation results this equivalent circuit model needs to be embedded with small wire-bond inductors and short 50Ω microstrip lines representing the line parts located within the reference planes shown in Fig. 3. This leads to the ADS simulation setup shown in Fig. 4 for the analysis of the assembled EML structure. The E/O transmission response is determined from a small-signal AC simulation as the ratio Vo/Vin. Similar to the experimental setup the structure is assumed to be driven from an 50Ω impedance, though this may not be optimal in terms of E/O transmission bandwidth.

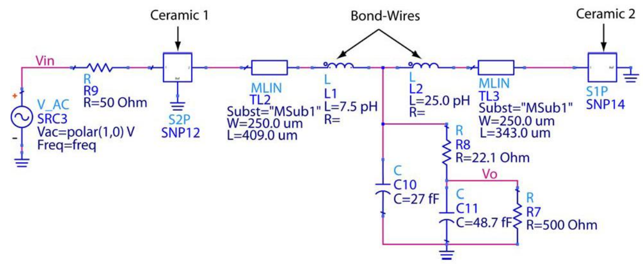


Fig. 4. ADS simulation setup for determining the E/O response of the integrated EML microstrip assembly.

Figure.5 compares the relative E/O response measured up to a frequency of 65 GHz with the results obtained from our proposed EM/circuit co-simulation approach. A very good agreement between measurements and the EM/circuit co-simulation is obtained over the measured bandwidth. A -3dB bandwidth of approximately 61GHz is predicted from simulation with a 35Ω load compared with approximately 60GHz for the experimental result. Both the experimental results and the simulated response show wide variations in the transmission characteristic with a dip at 32 GHz. This wave-like behavior is also observed with a dip at a slightly higher frequency in the case of a 50Ω load but not as significant.

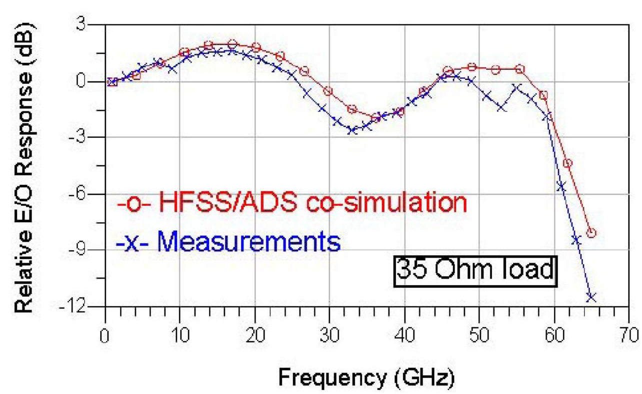


Fig. 5. Comparison between measured and simulated relative E/O transmission response for EML microstrip assembly.

In order to further investigate the cause of this non-ideal wave-like behavior we make use of our EM/circuit co-simulation approach. The idea is to substitute, in turn, the EM simulation results for the input and output ceramics, represented as S-parameter data blocks in Figure. 4 with ideal simulation components and observe the impact on the relative E/O transmission response. The equivalent circuit model representing the wire-bonded EML is kept unchanged in all investigations. First the output ceramic containing the microstrip line connecting the loads to the EML is substituted with ideal ohmic loads in the circuit simulation. The S-parameters data block containing the EM results of the input ceramic are kept in this investigation. Next the input ceramic containing the coplanar-to-microstrip transition and the microstrip line connecting the EML is substituted with an ideal through. In this case the S-parameters data block containing the EM results for the output ceramic is kept unchanged. In Fig. 6 it is shown how the ideal loads effectively remove the wave-like behavior in the relative E/O response and slightly increase the bandwidth. The use of an ideal through for the input ceramic acts to increase the relative E/O response at higher frequency but still shows the wave-like behavior. It can therefore be concluded that the wave-like behavior is caused by the output ceramic. Actually, the wave-like behavior occurs due to the reflection originating from the mismatch to the driving 50Ω microstrip line on the alumina substrate. In the future hybrid integration of the EML with its driving electronics this reflection should be eliminated.

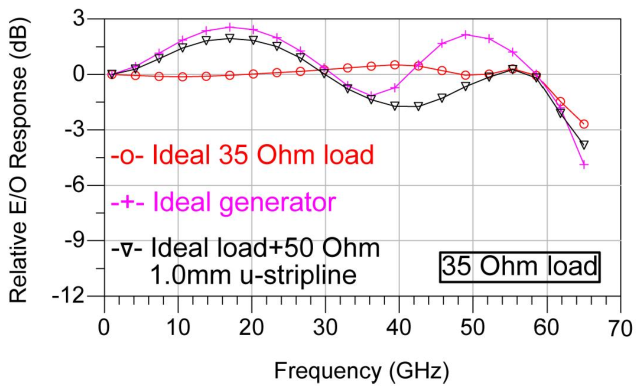


Fig. 6. Investigation of relative E/O transmission response for EML microstrip variations.

## V. Conclusion

In the present paper an improved electromagnetic simulation (EM) approach has been described for the investigation of the electrical and optical properties of hybrid integrated electro-absorption modulated lasers (EMLs) aiming at 100Gbit/s Ethernet applications. The EM based analysis allows for a realistic prediction of the performance of a microstrip assembly of a monolithically integrated EML which demonstrated state-of-the-art bandwidth capability of 60 GHz employing 35Ω loads. An undesired variation in the measured electrical to optical transmission response of the hybrid integrated EML as a function of frequency was successfully explained using the proposed EM based approach. The EM-based approach currently serves as a vehicle for the optimization of the future hybrid integration scheme of the EML with its driving electronics.

## Acknowledgement

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