

METHOD AND SYSTEM FOR DETERMINING AN OPTICAL EYE DIAGRAM OF A MODULATED OPTICAL BEAM OF AN INTERFEROMETER DEVICE

FIELD OF INVENTION

5 The present invention relates broadly to a method and a system for determining an optical eye diagram of a modulated optical beam of an interferometer device, to a method of evaluating system performance of electro-optic devices, and to a data storage medium having stored thereon data code means for instructing a computing device to execute the methods.

10 BACKGROUND

Current developments of high speed electro-optic devices cater to the continuously increasing complexity with a desire for large bandwidth requirements of current interconnect technology. The limitations faced by conventional copper interconnect are being readily recognized and thus the focus is being shifted to the optical interconnect lead by silicon photonics for its low
15 fabrication cost, electro-optic integration and CMOS compatibility.

Electro-optic devices typically work in interferometer configuration to modulate the optical intensity. The qualitative analysis of the modulated signal requires an eye diagram which gives at-glance evaluation of the system performance. Presently, researchers and industries use either the measured eye diagram or evaluate the measured eye diagram using system level
20 assumptions. For example, modulators in Mach-Zehnder interferometer (MZI) configuration are mostly measured for their eye diagram.

Figure 1 illustrates a typical eye diagram measurement setup 100. Figure 2 illustrates an implementation of a conventional method for determining the optical eye diagram. A random bit sequence generator 200 is applied to the device design 202 to modulate an un-modulated
25 optical beam 204. The modulated signal of the fabricated device for example using the set-up shown in Figure 1, to measure the optical eye diagram 206.

The existing methods and system suffer from the need for costly equipment in existing design iteration, e.g. spectrum analyzer, pseudo random binary sequence (PRBS) generator etc., as well as concerns that the analysis is not close enough to the actual system performance,
30 particularly when there is significant dependence on the operation speed.

Embodiments of the present invention provide a method and a system for determining an optical eye diagram of a modulated optical beam of an interferometer device, a method of evaluating system performance of electro-optic devices, and a data storage medium having stored thereon data code means for instructing a computing device to execute the methods that
35 seek to address at least one of the above problems.

SUMMARY

5 In accordance with a first aspect of the present invention, there is provided a method of determining an optical eye diagram of a modulated optical beam of an interferometer device, the method comprising obtaining AC parameters for one or more modulator structures of the interferometer device at respective DC bias voltages within a predetermined bias voltage range at an operating frequency of the one or more modulator structures from electrical simulation; obtaining a carrier concentration profile from the electrical simulation; obtaining optical parameters for the one or more modulator structures from optical simulation based on the carrier concentration profile; and determining the optical eye diagram of the modulated optical beam based on the AC parameters and the optical parameters.

10 In accordance with a second aspect of the present invention, there is provided a method of evaluating system performance of electro-optic devices, the method comprising performing the method of determining an optical eye diagram of a modulated optical beam of an interferometer device as defined in the first aspect.

15 In accordance with a third aspect of the present invention, there is provided a system for determining an optical eye diagram of a modulated optical beam of an interferometer device, the system comprising means for obtaining AC parameters for one or more modulator structures of the interferometer device at respective DC bias voltages within a predetermined bias voltage range at an operating frequency of the one or more modulator structures from electrical simulation; means for obtaining a carrier concentration profile from the electrical simulation; means for obtaining optical parameters for the one or more modulator structures from optical simulation based on the carrier concentration profile; and means for determining the optical eye diagram of the modulated optical beam based on the AC parameters and the optical parameters.

20 In accordance with a fourth aspect of the present invention, there is provided a data storage medium having stored thereon data code means for instructing a computing device to execute the method as defined in the first or second aspects.

BRIEF DESCRIPTION OF THE DRAWINGS

30 Embodiments of the invention will be better understood and readily apparent to one of ordinary skill in the art from the following written description, by way of example only, and in conjunction with the drawings, in which:

Figure 1 illustrates a typical eye diagram measurement setup;

35 Figure 2 illustrates an implementation of a conventional method for determining the optical eye diagram;

Figure 3 illustrates an example implementation of a method according to one embodiment;

Figure 4 shows a flow chart illustrating determining an eye diagram of the modulated optical beam of interferometer devices using electrical and optical simulation results of the individual modulator components, according to an example embodiment;

Figure 5 shows a representative block diagram of an implementation of a method according to another embodiment;

Figure 6 shows the schematic SOI modulator structure;

Figure 7 shows resultant optically modulated beam signal determined by a method according to an example embodiment, plotted as the eye diagram;

Figure 8 shows the measured eye diagram for an MZI and the biasing conditions used in the method for determining the eye diagram of Figure 7.

Figure 9 shows a flow chart illustrating a method of determining an optical eye diagram of a modulated optical beam of an interferometer device, according to an example embodiment.

Figure 10 shows a schematic drawing illustrating a system for determining an optical eye diagram of a modulated optical beam of an interferometer device, according to an example embodiment.

DETAILED DESCRIPTION

Embodiments of the present invention seek to provide a low cost, fast and accurate way of determining an eye diagram of high speed devices for evaluation of system performance. It has been recognized by the inventors that to understand the suitability for a particular speed, the use of data from electrical simulation, optical simulation and subsequent evaluation of the eye diagram from these electrical and optical simulation parameters is advantageous as it provides an analysis that can preferably be more close to the actual system performance. This becomes particularly crucial when there is significant dependence on the operation speed, where the inventors have recognized that to evaluate the effect of electrical and optical matrices separately is advantageous.

In embodiments of the present invention, in general a method of determining an optical eye diagram for an interferometer is described, wherein the electrical response of each arm of a modulator to an electrical pulse sequence is calculated separately. The optical response of each arm of the modulator is then calculated separately and the optical response of each arm of the modulator is combined to determine the modulated optical beam. The proposed method advantageously reduces the need for costly equipment needed in existing design iteration, e.g. spectrum analyzer, PRBS generator etc..

Figure 3 illustrates an example implementation of a method according to one embodiment. The performance of MZI type devices is evaluated by determining their eye diagram 300 from electrical simulations 302 and optical simulations 304 of component modulators from a

component library 306 for their respective device length. Example embodiments directly take into account the characteristics of the modulated optical beam, and provide high accuracy and clear insight into the modulation characteristics of the device. This advantageously enables designers and researchers to perform design iterations with full accuracy assured.

- 5 In one embodiment described herein, developed code is used in generating or determining the eye diagram for MZI comprising two p-i-n modulators. However, it will be appreciated that the present invention can be extended to any other type of modulator in different embodiments, such as ring resonators, and detectors with different length and driving in condition. Embodiments of the present invention can also accommodate any DC phase shift
10 included in the MZI configuration.

Figure 4 shows a flow chart 400 illustrating determining an eye diagram of the modulated optical beam of interferometer devices using electrical and optical simulation results of the individual modulator components. The method in this embodiment comprises the following steps.

- 15 Step 402: Obtaining AC parameters, such as AC capacitance and conductance, at every DC bias voltage from electrical simulation;

Step 404: Obtaining the carrier (electron and hole) concentration profile from the electrical simulation and converting the electron and hole concentration matrix into a matrix for the complex refractive index (refractive index and absorption coefficient);

- 20 Step 406: Using optical simulation to obtain optical parameters, namely the effective refractive index and loss, for the modulator structure, based on the device length and wavelength.

- Step 408: Together with the AC parameters, the optical parameters are used to determine the eye diagram of the modulated optical beam, based on simulated beam amplitude and
25 phase.

Figure 5 shows a representative block diagram of an implementation of a method according to another embodiment.

- 1) Generate a random bit sequence using a random bit generator 500;
- 2) Convert the bit sequence into driving or modulating voltage 502 for the modulator
30 arms. The user can choose whether to drive one or more of the arms;
- 3) Choose a time step according to the device operation speed.
- 4) Using time constant τ (obtained from electrical simulations 504) corresponding to the input voltage, calculate the instantaneous voltage across the capacitor, i.e. the transient response of the modulating voltage 506;

Repeat step 4) for both/all the arms of the modulator. Add the random noise to the voltage signal as found in the typical devices, as understood in the art;

The electrical eye diagram 508 is thus obtained;

- 5) For the instantaneous voltage obtained in step 4) calculate the amplitude and phase change of the optical beam using the data obtained from optical simulations 510;

Repeat step 5) for both/all the arms of the modulator;

- 6) Combine to the optical beams using their amplitude and phase values; and

- 7) Display the output beam intensity by overlapping them after every period i.e. the optical eye 512 is thus obtained.

- 10 The electrical response of each arm of the modulator to the electrical pulse sequence, see step 4) above, can be calculated according to following steps:

- Calculate the AC parameters 514, such as conductance (G) and capacitance (C), from the electrical simulation 504 for every DC bias voltage in the desired range of operating voltage and at frequency (f) of operation;

- 15 • Calculate the time constant ($\tau = C/G$) for every DC bias voltage.

The optical response of each arm of the modulator, see step 5) above, can be calculated separately according to the following steps:

- Calculate the optical parameters 516, such as effective refractive index and propagation loss, for every DC bias voltage;

- 20 • Choose the device length and operating wavelength;

- Calculate the phase change and loss (amplitude reduction) of the optical beam for every DC bias voltage.

The optical response of each arm of the modulator is combined to get the modulated optical beam 518 by adding the output beams from two/all arms (addition according to amplitude and phase).

- 25 The carrier (electron and hole) concentration profile 520 is obtained from the electrical simulation 504 and the electron and hole concentration matrix is converted into a matrix for the complex refractive index (refractive index and absorption coefficient) for use in the optical simulation 510 in the example embodiment. The electrical simulation 504 and the
- 30 optical simulation 510 are based on data from a component library 522.

Embodiments of the present invention have been successfully applied to MZI configuration comprising a silicon-on-insulator (SOI) modulator.

Figure 6 shows the schematic SOI modulator structure 600. The electrical simulations have been performed for 0V-to-10V reverse bias voltages. AC capacitance and conductance are used to calculate the step response of each modulator arm. Optical simulations are performed, using the carrier profiles obtained from the electrical simulations for 0V-10V reverse bias, to calculate the effective refractive index and loss for each modulator arm.

A random bit sequence, with 10 Gb/s data rate, has been applied to the two modulator arms arranged in MZI configuration. The modulator arm e.g. 602 is 2 mm long with the input of DC bias, $V_{dc} = -3.75$ V, and rf signal, $V_{rf} = 5$ Vpp. Depending on the bit value, input to the modulator arm 602 consists of either $V_{dc} \pm V_{rf}/2$. The electrical response of the individual arm is simulated using the electrical capacitance/conductance parameters. Using the electrical response of each arm, its effect on the optical beam's magnitude and phase is calculated using the effective refractive index and loss values obtained from the optical simulations at the relevant bias voltage. The resultant optically modulated beam signal is plotted as the eye diagram 700 in Figure 7.

In order to validate the simulated eye diagram, Figure 8 shows the measured eye diagram 800 for MZI and the biasing conditions described above, illustrating close agreement.

Figure 9 shows a flow chart 900 illustrating a method of determining an optical eye diagram of a modulated optical beam of an interferometer device, according to one embodiment. At step 902, AC parameters for one or more modulator structures of the interferometer device are obtained at respective DC bias voltages within a predetermined bias voltage range at an operating frequency of the one or more modulator structures from electrical simulation. At step 904, a carrier concentration profile is obtained from the electrical simulation. At step 906, optical parameters for the one or more modulator structures are obtained from optical simulation based on the carrier concentration profile. At step 908, the optical eye diagram of the modulated optical beam is determined based on the AC parameters and the optical parameters.

The AC parameters may comprise the AC conductance and the AC capacitance.

The optical parameters may comprise the effective refractive index and loss.

The obtaining of the optical parameters may comprise obtaining a matrix for the complex refractive index for the one or more modulator structures from the carrier concentration profile, converting the matrix for the complex refractive index into a matrix for the complex refractive index for the one or more modulator structures, and obtaining the optical parameters for the one or more modulator structures from the optical simulation. The obtaining the optical parameters may be based on a device length of the respective modulator structures and a relevant wavelength.

Determining the optical eye diagram of the modulated optical beam may be further based on simulated beam amplitude and phase in the one or more arms of the interferometer associated with the one or more modulator structures respectively.

The method may comprise obtaining a time constant τ from the AC parameters corresponding to a modulating voltage signal for the one or more modulator structures; and calculating a transient response of the modulating voltage signal for the one or more modulator structures based on a time step chosen according to an operation speed of the one or more modulators.

- 5 The method may comprise adding random noise to the modulating voltage signal. The modulating voltage signal is converted from a random bit sequence generated using a random bit generator. The method may comprise obtaining an electrical eye diagram based on the transient response of the modulating voltage signal for the one or more modulator structures. The method may comprise calculating amplitude and phase change of the modulated optical
10 beam for the one or more modulator structures using data obtained from the optical simulations. The method may comprise combining the optical beams in the interferometer device using their respective amplitude and phase values, and displaying an output beam intensity by overlapping the optical beams after every period.

- 15 In one embodiment, a method of evaluating system performance of electro-optic devices is provided, the method comprising performing the method of determining an optical eye diagram of a modulated optical beam of an interferometer device as described in the above embodiment with reference to Figure 9.

- Figure 10 shows a schematic drawing illustrating a system 1000 for determining an optical eye diagram of a modulated optical beam of an interferometer device, according to one
20 embodiment. The system comprises means for obtaining AC parameters for one or more modulator structures of the interferometer device at respective DC bias voltages within a predetermined bias voltage range at an operating frequency of the one or more modulator structures from electrical simulation, 1002, means for obtaining a carrier concentration profile from the electrical simulation, 1004, means for obtaining optical parameters for the one or
25 more modulator structures from optical simulation based on the carrier concentration profile, 1006, and means for determining the optical eye diagram of the modulated optical beam based on the AC parameters and the optical parameters, 1008.

The AC parameters may comprise the AC conductance and the AC capacitance.

The optical parameters may comprise the effective refractive index and loss.

- 30 The means for obtaining of the optical parameters, 1006, may be configured to obtain a matrix for the complex refractive index for the one or more modulator structures from the carrier concentration profile, convert the matrix for the complex refractive index into a matrix for the complex refractive index for the one or more modulator structures, and obtain the optical parameters for the one or more modulator structures from the optical simulation. The
35 obtaining the optical parameters may be based on a device length of the respective modulator structures and a relevant wavelength.

The means for determining the optical eye diagram of the modulated optical beam, 1008, may be configured to determine the optical eye diagram further based on simulated beam

amplitude and phase in the one or more arms of the interferometer associated with the one or more modulator structures respectively.

5 The system may comprise means for obtaining a time constant τ from the AC parameters corresponding to a modulating voltage signal for the one or more modulator structures, and means for calculating a transient response of the modulating voltage signal for the one or more modulator structures based on a time step chosen according to an operation speed of the one or more modulators. The means for obtaining the time constant is configured for adding random noise to the modulating voltage signal. The system may comprise means for converting the modulating voltage signal from a random bit sequence generated using a random bit generator. The system may comprise means for obtaining an electrical eye diagram based on the transient response of the modulating voltage signal for the one or more modulator structures. The system may comprise means for calculating amplitude and phase change of the modulated optical beam for the one or more modulator structures using data obtained from the optical simulations. The system may comprise means for combining the optical beams in the interferometer device using their respective amplitude and phase values, and displaying an output beam intensity by overlapping the optical beams after every period.

In one embodiment, a data storage medium is provided having stored thereon data code means for instructing a computing device to execute the method as described in the above embodiments.

20 According to the various embodiments, the proposed implementations of the methods are able to calculate very accurately the high-speed optical eye diagram performance based on the actual device dimension and dopant topology - an effect which the existing measurement and estimation cannot provide.

Embodiments of the present invention permit accurate analysis of the modulated optical signal using MZI type configuration of modulators, giving an unprecedented ability to determine the eye diagram from electrical and optical simulation characteristics of individual modulator components. The methodology in the example embodiments includes obtaining the AC capacitance and conductance from electrical simulations and the effective complex refractive index from optical simulations, which are used to model the phase change and loss induced by each modulator along with the time response determined by the electrical AC parameters. Embodiments of the present invention are suitable for interferometer optical device level analysis as well as system level analysis using characteristics of individual components.

Industrial application:

35 Eye diagram determination will be helpful in determining the operation speed of modulators (such as MZI, ring resonators etc) and detectors, DC bias voltages and AC voltage swing.

The method of example embodiments is very fast and economical for its ability to determine the eye diagram of the modulated beam, compared to the traditional method of measuring the eye diagram from a fabricated device.

5 The code for one example embodiment can handle the different length of modulator arms, different bias voltages and existence of DC phase shifter, if necessary.

The code can be adopted in different embodiments for different types of modulator devices (such as electro-refractive, electro-absorptive and electro-optic) and optical systems.

The method of example embodiments can be applied to any arbitrary number of modulator arms, lengths and additional DC phase shifters.

10 The method of example embodiments can be applied to MZI configuration of p-i-n modulators to determine the eye diagram of a modulated optical beam. It can determine the eye diagram of modulated the optical beam for any type of modulator(s)/detectors, their length, number of modulating arms, single-ended or double-ended operation for any speed. The method of example embodiments performs substantially better than the traditional way of
15 measuring the eye diagram or approximating the system level simulation of eye diagram without obtaining actual parameters, including actual device dimensions and dopant topology, from simulations of individual components.

The method of example embodiments can determine the eye diagram of electro-optic modulator, which in turn translates to cost saving for PRBS generator and high speed
20 oscilloscope by at least \$200k for 10 Gbps, which will increase exponentially with higher bit rate.

The present specification also discloses an apparatus for performing the operations of the methods. Such apparatus may be specially constructed for the required purposes, or may comprise a general purpose computer or other device selectively activated or reconfigured by
25 a computer program stored in the computer. The algorithms and displays presented herein are not inherently related to any particular computer or other apparatus. Various general purpose machines may be used with programs in accordance with the teachings herein. Alternatively, the construction of a more specialized apparatus to perform the required method steps may be appropriate. In addition, the present specification also implicitly discloses a computer
30 program, in that it would be apparent to the person skilled in the art that the individual steps of the method described herein may be put into effect by computer code. The computer program is not intended to be limited to any particular programming language and implementation thereof. It will be appreciated that a variety of programming languages and coding thereof may be used to implement the teachings of the disclosure contained herein.
35 Moreover, the computer program is not intended to be limited to any particular control flow. There are many other variants of the computer program, which can use different control flows without departing from the spirit or scope of the invention.

Furthermore, one or more of the steps of the computer program may be performed in parallel rather than sequentially. Such a computer program may be stored on any computer readable medium. The computer readable medium may include storage devices such as magnetic or optical disks, memory chips, or other storage devices suitable for interfacing with a computing device. The computer program when loaded and executed on the computing device effectively results in an apparatus that implements the steps of the preferred method.

The invention may also be implemented as hardware modules. More particular, in the hardware sense, a module is a functional hardware unit designed for use with other components or modules. For example, a module may be implemented using discrete electronic components, or it can form a portion of an entire electronic circuit such as an Application Specific Integrated Circuit (ASIC). Numerous other possibilities exist. Those skilled in the art will appreciate that the system can also be implemented as a combination of hardware and software modules.

It will be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive. Also, the invention includes any combination of features, in particular any combination of features in the patent claims, even if the feature or combination of features is not explicitly specified in the patent claims or the present embodiments.

CLAIMS

1. A method of determining an optical eye diagram of a modulated optical beam of an interferometer device, the method comprising:

obtaining AC parameters for one or more modulator structures of the interferometer device at respective DC bias voltages within a predetermined bias voltage range at an operating frequency of the one or more modulator structures from electrical simulation;

obtaining a carrier concentration profile from the electrical simulation;

obtaining optical parameters for the one or more modulator structures from optical simulation based on the carrier concentration profile; and

determining the optical eye diagram of the modulated optical beam based on the AC parameters and the optical parameters;

wherein the obtaining of the optical parameters comprises obtaining a matrix for the complex refractive index for the one or more modulator structures from the carrier concentration profile, converting the matrix for the complex refractive index into a matrix for the complex refractive index for the one or more modulator structures, and obtaining the optical parameters for the one or more modulator structures from the optical simulation.

2. The method as claimed in claim 1, wherein the AC parameters comprise the AC conductance and the AC capacitance.

3. The method as claimed in claims 1 or 2, wherein the optical parameters comprise the effective refractive index and loss.

4. The method as claimed in claim 1, wherein the obtaining the optical parameters is based on a device length of the respective modulator structures and a relevant wavelength.

5. The method as claimed in any one of the preceding claims, wherein determining the optical eye diagram of the modulated optical beam is further based on simulated beam amplitude and phase in the one or more arms of the interferometer associated with the one or more modulator structures respectively.

6. The method as claimed in any one of the preceding claims, comprising obtaining a time constant τ from the AC parameters corresponding to a modulating voltage signal for the one or more modulator structures, and calculating a transient response of the modulating voltage signal for the one or more modulator structures based on a time step chosen according to an operation speed of the one or more modulators.

7. The method as claimed in claim 6, comprising adding random noise to the modulating voltage signal.

8. The method as claimed in claims 6 or 7, the modulating voltage signal is converted from a random bit sequence generated using a random bit generator.

9. The method as claimed in any one of claims 6 to 8, comprising obtaining an electrical eye diagram based on the transient response of the modulating voltage signal for the one or more modulator structures.
10. The method as claimed in any one of claims 6 to 9, comprising calculating amplitude and phase change of the modulated optical beam for the one or more modulator structures using data obtained from the optical simulations.
11. The method as claimed in claim 10, comprising combining the optical beams in the interferometer device using their respective amplitude and phase values, and displaying an output beam intensity by overlapping the optical beams after every period.
12. A method of evaluating system performance of electro-optic devices, the method comprising performing the method of determining an optical eye diagram of a modulated optical beam of an interferometer device as claimed in any one of the preceding claims.
13. A system for determining an optical eye diagram of a modulated optical beam of an interferometer device, the system comprising:
- means for obtaining AC parameters for one or more modulator structures of the interferometer device at respective DC bias voltages within a predetermined bias voltage range at an operating frequency of the one or more modulator structures from electrical simulation;
 - means for obtaining a carrier concentration profile from the electrical simulation;
 - means for obtaining optical parameters for the one or more modulator structures from optical simulation based on the carrier concentration profile; and
 - means for determining the optical eye diagram of the modulated optical beam based on the AC parameters and the optical parameters;
- wherein the means for obtaining of the optical parameters is configured to obtain a matrix for the complex refractive index for the one or more modulator structures from the carrier concentration profile, convert the matrix for the complex refractive index into a matrix for the complex refractive index for the one or more modulator structures, and obtain the optical parameters for the one or more modulator structures from the optical simulation.
14. The system as claimed in claim 13, wherein the AC parameters comprise the AC conductance and the AC capacitance.
15. The system as claimed in claims 13 or 14, wherein the optical parameters comprise the effective refractive index and loss.
16. The system as claimed in claim 13, wherein the obtaining the optical parameters is based on a device length of the respective modulator structures and a relevant wavelength.
17. The system as claimed in any one of claims 13 to 16, wherein the means for determining the optical eye diagram of the modulated optical beam is configured to determine the optical eye

diagram further based on simulated beam amplitude and phase in the one or more arms of the interferometer associated with the one or more modulator structures respectively.

18. The system as claimed in any one of claims 13 to 17, comprising means for obtaining a time constant τ from the AC parameters corresponding to a modulating voltage signal for the one or more modulator structures, and means for calculating a transient response of the modulating voltage signal for the one or more modulator structures based on a time step chosen according to an operation speed of the one or more modulators.

19. The system as claimed in claim 18, wherein the means for obtaining the time constant is configured for adding random noise to the modulating voltage signal.

20. The system as claimed in claims 18 or 19, comprising means for converting the modulating voltage signal from a random bit sequence generated using a random bit generator.

21. The system as claimed in any one of claims 18 to 20, comprising means for obtaining an electrical eye diagram based on the transient response of the modulating voltage signal for the one or more modulator structures.

22. The system as claimed in any one of claims 18 to 21, comprising means for calculating amplitude and phase change of the modulated optical beam for the one or more modulator structures using data obtained from the optical simulations.

23. The system as claimed in claim 22, comprising means for combining the optical beams in the interferometer device using their respective amplitude and phase values, and displaying an output beam intensity by overlapping the optical beams after every period.

24. A data storage medium having stored thereon data code means for instructing a computing device to execute the method as claimed in any one of claims 1 to 12.