



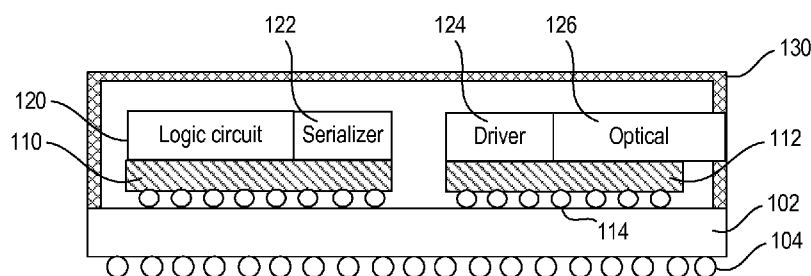
- (51) **International Patent Classification:**
H04B 10/50 (2013.01) *H04B 10/80* (2013.01)
- (21) **International Application Number:**
PCT/US2015/033598
- (22) **International Filing Date:**
1 June 2015 (01.06.2015)
- (25) **Filing Language:** English
- (26) **Publication Language:** English
- (30) **Priority Data:**
14/297,535 5 June 2014 (05.06.2014) US
14/297,527 5 June 2014 (05.06.2014) US
- (71) **Applicant:** XILINX, INC. [US/US]; Attn: Legal Dept,
2100 Logic Drive, San Jose, CA 95124 (US).
- (72) **Inventors:** LESEA, Austin, H.; 2100 Logic Drive, San
Jose, CA 95124 (US). TRIMBERGER, Stephen, M.;
2100 Logic Drive, San Jose, CA 95124 (US).
- (74) **Agents:** PARANDOOSH, David, A. et al.; Xilinx, Inc.,
Attn: Legal Dept., 2100 Logic Drive, San Jose, CA 95124
(US).

(81) **Designated States** (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) **Designated States** (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

(54) **Title:** OPTICAL COMMUNICATIONS CIRCUITS**FIG. 1**

(57) **Abstract:** Various apparatuses, circuits, systems, and methods for optical communication are disclosed. In some implementations, an apparatus includes a package substrate (102) and first interposer (110, 112) mounted on the package substrate. The apparatus also includes a logic circuit (120) and an optical interface circuit (124, 126) connected to the logic circuit via the first interposer. One of the optical interface circuit or the logic circuit is mounted on the first interposer. The optical interface circuit includes a driver circuit (124) configured to receive electronic data signals from the logic circuit. The optical interface circuit also includes an optical transmitter circuit (126) coupled to the driver circuit and configured to output optical data signals encoding the electronic data signals.



OPTICAL COMMUNICATION CIRCUITS

FIELD OF THE DISCLOSURE

The disclosure generally relates to high speed communication, and more
5 particularly to optical communication.

BACKGROUND

Fiber optics are used in a number of applications for high speed data
communication. Communication systems based on fiber optics transmit data as
10 modulated laser light through an optical fiber (e.g., glass or plastic). Fiber optic
communication systems are advantageous for many applications as noise is not
induced in the fiber by the presence of electromagnetic signals in the
environment.

15 SUMMARY

Various apparatuses, circuits, systems, and methods for optical
communication are disclosed. An apparatus is disclosed that includes a
package substrate and a first interposer mounted on the package substrate. The
apparatus also includes a logic circuit and an optical interface circuit connected
20 to the logic circuit via the first. One of the optical interface circuit or the logic
circuit is mounted on the first interposer. The optical interface circuit includes a
driver circuit configured to receive electronic data signals from the logic circuit.
The optical interface circuit also includes an optical transmitter circuit coupled to
the driver circuit and configured to output optical data signals encoding the
25 electronic data signals.

A method is also disclosed for manufacturing an apparatus having an
optical communication circuit. A logic circuit is mounted on a first interposer. An
optical interface circuit is formed on a second interposer by mounting an optical
transmitter circuit on the second interposer, mounting a driver circuit on the
30 second interposer, and connecting the driver circuit via wiring on the second
interposer. The first interposer is mounted on a substrate having one or more
wiring layers. The second interposer is mounted on the substrate. The logic
circuit die and the optical interface circuit are connected via the first interposer,
the one or more wiring layers, and the second interposer.

An apparatus having an optical serializer is also disclosed. The optical serializer includes a plurality of optical modulators. Each of the optical modulators is configured to receive a respective bit of a parallel multi-bit data bus in a first bit period. Each of the optical modulators is configured to output a
5 respective optical pulse representing the value of the respective bit. The optical pulse has a duration less than the first bit period. For each of the optical modulators, the optical serializer includes an optical delay line configured to delay the optical pulses output from the optical modulator to produce a
10 respective optical output signal. Each optical delay line delays pulses by a respective length of time unique to the optical modulator connected thereto. The optical serializer also includes an optical combiner configured to combine the respective optical output signals produced by the optical delay line into a single optical beam.

A method for optical serialization is also disclosed. For each bit of parallel
15 multi-bit data bus transmitted in a first bit period, a respective optical modulator is used to provide a respective optical pulse. The optical pulse has a duration less than the first bit period. Each of the respective optical pulses is delayed by a respective length of time unique to the optical modulator to produce a respective optical output signal. The respective optical output signals are
20 combined into a single optical beam.

Other features will be recognized from consideration of the Detailed Description and Claims, which follow.

BRIEF DESCRIPTION OF THE DRAWINGS

25 Various aspects and features of the disclosed methods, circuits, and systems will become apparent upon review of the following detailed description and upon reference to the drawings in which:

FIG. 1 shows an IC package including a logic circuit and a serializer circuit mounted on a substrate via a first interposer and an optical interface
30 circuit mounted on the substrate via a second interposer;

FIG. 2 shows an IC package including a logic circuit and a serializer circuit mounted directly on a substrate and an optical interface circuit mounted on the substrate via an interposer;

FIG. 3 shows an IC package including a logic circuit and a serializer circuit mounted on a substrate via an interposer and an optical interface circuit mounted directly on the substrate;

FIG. 4 shows an IC package including a logic circuit mounted on a substrate via a first interposer and a serializer and optical interface circuits mounted on the substrate via a second interposer;

FIG. 5 shows an IC package including a logic circuit mounted directly on a substrate and a serializer and optical interface circuits mounted on the substrate via an interposer;

FIG. 6 shows an IC package including a logic circuit mounted on a substrate via an interposer and a serializer and optical interface circuits mounted directly on the substrate;

FIG. 7 shows an optical serializer, in accordance with one or more implementations;

FIG. 8 shows a configurable optical transmitter, in accordance with one or more implementations; and

FIG. 9 shows an apparatus configured to select between a plurality of lasers for frequency modulation, amplitude modulation, and/or based on operating temperatures of the apparatus;

FIG. 10 shows a process for communicating using multiple lasers;

FIG. 11A illustrates an optical data port having an array of communication circuits for communication over an optical fiber;

FIG. 11B illustrates alignment of an optical fiber with a single communication circuit;

FIG. 11C illustrates alignment of an optical fiber with an array of communication circuits;

FIG. 12 shows a process for automated alignment of an optical fiber using an array of communication circuits;

FIG. 13 shows various non-circular optical fiber ends that may be used for alignment of an optical fiber;

FIG. 14 shows a system for communication using optical differential signals; and

FIG. 15 shows a FPGA package that may be configured in accordance with one or more implementations.

DETAILED DESCRIPTION OF THE DRAWINGS

Various aspects of the present disclosure are believed to be applicable to a variety of different types of apparatuses, circuits, systems, and methods
5 involving optical communication.

Various integrated circuit (IC) packages are disclosed that include a logic circuit and an optical communication circuit. One or both of the logic circuit and optical communication circuit are assembled on respective interposers for later mounting and connection in an IC package. This allows the logic circuit and
10 optical communication circuit assemblies to be separately manufactured and tested prior to final assembly in an IC package. Accordingly, flawed logic circuits and/or optical communication circuits can be identified before being manufactured into the final IC package. In this manner, the production yield for manufacture of the IC package is increased.

15 The disclosed implementations are applicable IC packages including various logic circuits in combination with an optical communication circuit. For example, in some applications, the logic circuit may include a programmable IC. For ease of explanation, the examples in the disclosure may be generally discussed with reference to an IC package including an electronic logic circuit
20 (e.g., a programmable IC) and an optical communication circuit.

In some implementations, a logic circuit and a serializer circuit are mounted on a first interposer and an optical interface circuit is mounted on a second interposer. The first and second interposers are mounted on a package substrate having one or more wiring layers. The serializer circuit is connected to
25 the optical interface circuit via the first and second interposers and the wiring layers.

In some implementations, the optical interface circuit may include both an optical transmitter and a driver configured to provide electronic data signals to the optical transmitter for transmission. Some optical communication circuits
30 include a driver connected to an optical transmitter, and both the driver and optical transmitter are mounted directly on a package substrate and connected via wiring layers on the substrate. However, high speed communication through the wiring layers can dissipate a significant amount of power. By including the optical transmitter and the driver on the same interposer, the transmission line

distance between the optical transmitter and the driver is reduced and power efficiency improved. In some implementations, signal lines between the optical transmitter and the driver have lengths less than or equal to $1/8$ the wavelength of a highest frequency of the data signals.

5 In some implementations, the serializer circuit may instead be mounted on the second interposer with the optical interface circuit. By integrating the serializer circuit with the optical communication circuit on the same interposer, the data rate of the serializer circuit is not limited by the transmission through wiring layers of the substrate (*e.g.*, 100 ohm differential signal lines). The logic
10 circuit is connected to the serializer circuit by several parallel channels via the first interposer, the wiring layers on the substrate, and the second wiring layers. The serializer circuit is connected to the driver via wiring on the second interposer.

In some implementations, for example, the serializer circuit and the driver
15 are connected by signal lines having lengths less than or equal to $1/8$ the wavelength of a highest frequency used by the serializer circuit to provide the serial data to the driver circuit. Use of signal lines having lengths less than or equal to $1/8$ the wavelength allows signal lines to be implemented with higher impedances than the 100 ohm differential signal lines included in the wiring
20 layers on the substrate.

Although the examples and implementations are primarily discussed with reference to a serializer circuit that provides serialized data for transmission by an optical transmitter, the implementations are not so limited. For instance, the disclosed examples and implementations may be adapted for an optical receiver
25 by replacing the serializer with a deserializer and replacing the optical transmitter with an optical receiver. Furthermore, the disclosed examples and implementations may be adapted for a transceiver configured to transmit and receive optical data. In such implementations, the serializer is replaced by a serializer/deserializer circuit (Serdes). For ease of explanation, the examples
30 and implementations are primarily discussed with reference to a serializer that provides serialized data for transmission by an optical transmitter. In some implementations, one of the two interposers may be omitted. For example, the first interposer may be omitted and the logic circuit may be mounted directly on

the substrate. Conversely, the second interposer may be omitted and the optical interface circuit may be mounted directly on the substrate.

Turning now to the figures, FIG. 1 shows a first IC package configured in accordance with one or more implementations. In this example, a logic circuit 120 and a serializer circuit 122 are mounted on a first interposer 110. An optical interface circuit, including a driver circuit 124 and an optical transmitter 126, is mounted on a second interposer 112. The interposers include contacts 114 (e.g., microbumps) for connecting the circuits mounted thereon with external circuits. The first and second interposers are mounted on a substrate 102 of the package. The logic circuit and serializer circuit may be communicatively coupled to one with another by wiring layers (not shown) in the interposer 110 and also communicatively coupled to the substrate by way of through-silicon vias (not shown) and wiring layers in the interposer and the contacts 114. Driver circuit 124 and optical transmitter 126 are similarly communicatively coupled to one with another by wiring layers (not shown) in the interposer 112. The substrate includes one or more wiring layers (not shown) for interconnecting the interposers and external package terminals 104 (e.g., solderballs). In this example, the circuits are encapsulated by a package cover 130. Alternatively or additionally, a molding compound may be disposed over the circuits. In this example, the optical transmitter extends through the package cover 130 to provide an optical data on the side of the package cover.

FIG. 2 shows a second IC package configured in accordance with one or more implementations. The IC package in this example includes components that are similar to those of the IC package shown in FIG. 1, as indicated by the reference numbers. In this example, the logic circuit 120 and serializer circuit 122 are not mounted on an interposer (e.g., 110). Rather, the logic circuit 120 and serializer circuit 122 are directly mounted on the substrate 102.

FIG. 3 shows a third IC package configured in accordance with one or more implementations. The IC package in this example includes components that are similar to those of the IC package shown in FIG. 1, as indicated by the reference numbers. In this example, the optical communication circuit (*i.e.*, the driver circuit 124 and the optical transmitter 126) is not mounted on an interposer. Rather, the optical communication circuit is directly mounted on the substrate 102.

FIG. 4 shows a fourth IC package configured in accordance with one or more implementations. In this example, a logic circuit is mounted on a first interposer 410. An optical interface circuit, including a serializer circuit 422, a driver circuit 424, and an optical transmitter 426, is mounted on a second interposer 412. The interposers include contacts 414 (e.g., microbumps) for connecting the circuits mounted thereon with external circuits. The first and second interposers are mounted on a substrate 402 of the package. The substrate includes one or more wiring layers (not shown) for interconnecting the interposers and external package terminals 404 (e.g., solderballs). In this example, the circuits are encapsulated by a package cover 430.

FIG. 5 shows a fifth IC package configured in accordance with one or more implementations. The IC package in this example includes components that are similar to those of the IC package shown in FIG. 4, as indicated by the reference numbers. In this example, the logic circuit 420 is not mounted on an interposer (e.g., 410). Rather, the logic circuit 420 is directly mounted on the substrate 402.

FIG. 6 shows a sixth IC package configured in accordance with one or more implementations. The IC package in this example includes components that are similar to those of the IC package shown in FIG. 4, as indicated by the reference numbers. In this example, the optical communication circuit (i.e., the serializer circuit 422, the driver circuit 424, and the optical transmitter 426) is not mounted on an interposer. Rather, the optical communication circuit is directly mounted on the substrate 402.

Apparatuses and methods for serializing optical data signals are also disclosed. In some implementations, an optical serialization circuit includes a plurality of optical modulators. Each of the optical modulators is configured to receive a respective bit of a parallel multi-bit data bus in a first bit period. Each optical modulator is further configured to output a respective optical pulse representing the value of the received bit and having a duration less than the first bit period. For an N-bit data bus, the duration may be, for example, the first bit period divided by N.

The optical serialization circuit also includes a set of optical delay lines. Each delay line is configured to delay optical pulses produced by one of the optical modulators by a respective length of time unique to the optical modulator

to produce a respective optical output signal. In some implementations, the respective lengths of time are multiples of the duration of the optical pulses. An optical combiner is configured to combine the optical output signals to produce a single optical output beam.

5 In some implementations, the single output beam is transmitted through an optical fiber to an optical deserializer. The optical deserializer is configured to receive the single optical beam and separate the optical output signals from the single optical beam. The optical deserializer is further configured to provide the optical output signals as respective bits of a parallel data bus.

10 Turning again to the figures, FIG. 7 shows an optical serializer, in accordance with one or more implementations. The optical serializer comprises a plurality of optical modulators 720, 722, 724, and 726, which may be controllable lasers or optical multiplexors, such as Mach-Zehnder modulators. Each of the optical modulators is configured to receive a respective bit of an
15 electrical N-bit data bus 702 in each bit period 710. Each optical modulator is configured to output a respective optical pulse 750 representing the value of the received bit. Example output pulses 750 produced by the optical modulators 720, 722, 724, and 726 are shown by waveforms 712. In this example, each of the output pulses has a duration equal to $1/N$ of the bit period 710.

20 The optical serializer also includes a set of optical delay lines 730, 732, 734, and 736. Each optical delay line is configured to delay the optical pulses output by each optical modulator by a respective length of time unique to the optical modulator to produce a respective optical output signal 752. In this example, each of the optical delay lines delays optical pulses by a respective
25 multiple of the duration of the output pulses (*i.e.*, bit period/ N). Example output signals 752 are shown by waveforms 714. As illustrated by waveforms 714, each output pulse coincides with a respective time period. An optical combiner 740 is configured to combine the output signals 752 to produce a combined output signal 754.

30 Apparatuses and methods are disclosed for providing a configurable optical channel with user configurable parameters. In some implementations, an optical transmitter circuit includes a set of optical communication circuits, each configured to communicate optical data according to a different configuration of a parameter (*e.g.*, modulation, data rate, frequency, polarization, and/or phase).

The optical transmitter circuit includes a selection circuit that is configured to select one of the set of optical communication circuits for operation in response to a first control signal. By selecting different ones of the set of optical communication circuits at different times, the operation of the optical transmitter
5 circuit can be adjusted by way of the different configurations of the parameter.

In some implementations, the set of optical communication circuits may include a plurality of lasers exhibiting respective characteristics. For example, in some implementations, each laser produces light of a respective frequency. By selecting different ones of the lasers for operation, frequency of an optical data
10 signal produced by the optical transmitter may be adjusted.

As another example, the set of optical communication circuits includes a plurality of optical delay lines, each configured to delay an optical data signal produced by the optical transmitter circuit by a different amount of time. By selecting different ones of the optical delay lines, a phase of an optical data
15 signal output by the optical transmitter may be adjusted.

Turning again to the figures, FIG. 8 shows a configurable optical transmitter, in accordance with one or more implementations. In this example, the transmitter includes an electronic driver 804 configured to provide an electronic signal to a plurality of lasers 810, 812, and 814 for transmission. Each
20 of the lasers is configured to output a respective optical data signal, encoding the electronic signal. Each of the lasers exhibits a unique configuration of an optical parameter. For instance, the lasers may exhibit respective frequencies, temperature ranges, and/or light intensities. The transmitter includes a selection circuit configured to select one of the lasers for operations. In this example, the
25 selection circuit includes an optical multiplexor 818 configured to output an optical data signal from one of the lasers that is selected by control circuit 802. The optical multiplexor 818 blocks optical data signals from other ones of the lasers. In some other implementations, the selection circuit may include a circuit configured to enable a selected one of the lasers and disable non-selected ones
30 of the lasers. An optical combiner may be used in lieu of an optical multiplexor 818 to merge optical data signals from the selected ones of the lasers.

In some implementations, the control circuit 802 may also adjust the configuration of various parameters of the electronic driver circuit 804. For example, the electronic driver circuit 804 may be configured to adjust

transmission rate and/or modulation algorithm used to encode data values (e.g., amplitude/frequency modulation) in response to control signals from the control circuit 802.

5 In this example, the optical transmitter also includes a set of optical components 822, 824, and 826 that may be selected to configure one or more optical parameters of an optical data signal. The set of optical components 822, 824, and 826 may include, but are not limited to, optical delays, polarization filters, and/or spectrum filters.

10 In this example, an optical demultiplexor 820 is configured to provide an optical data signal to one of the optical components 822, 824, and 826, which is selected by the control circuit 802. An optical multiplexor 828 is configured to output an optical data signal from the one of the optical components 822, 824, and 826, which is selected by the control circuit 802. The optical multiplexor transmits the selected optical data signal over an optical fiber 832.

15 In this example, the transmitter includes two respective sets of circuits that may be selected for operation (e.g., the set of lasers 810, 812, and 814; and the set of optical components 822, 824, 826). In some implementations, a transmitter may only include one set of circuits that may be selected for operation (e.g., either the set of lasers or the set of components). Conversely, in
20 some implementations, a transmitter may include three or more respective sets of circuits that may be selected for operation. In some implementations, optical modulators, such as Mach-Zehnder modulators, may be controlled in place of the lasers, wherein the optical modulators control the intensity of laser light sent to optical multiplexor 818.

25 Various optical communication circuits are also disclosed herein and include a plurality of optical communication circuits for modulation and/or configuration of various parameters of a light beam produced by the lasers. For example, in some implementations, an optical transmitter includes an optical data port configured to engage an optical fiber. The optical transmitter also
30 includes a plurality of optical communication circuits, each configured to transmit respective optical signals over the optical fiber via the optical data port when selected. The optical communication circuits may include, for example, lasers, optical modulators, or optical waveguides to transmit optical signals. A control

circuit may be configured to select various ones of the optical communication circuits for transmission of light beams over the optical fiber.

In several implementations, the optical communication circuits include a plurality of lasers. In some implementations, the control circuit is configured to
5 adjust an amplitude/intensity of a light beam output from the transmitter by selecting different numbers of the lasers for transmission of light over the optical fiber at the same time. The control circuit may be further configured to select the lasers to encode a data signal by modulating the amplitude/intensity of the combined laser beams output by the transmitter.

10 In some implementations, each of the lasers is configured to produce light of a respective frequency. The control circuit may select different ones of the lasers to adjust a frequency of a light beam output by the transmitter. The control circuit may be configured to select the lasers to encode a data signal by modulating a frequency of the light beam output by the transmitter.

15 Different ones of the lasers may operate correctly over different temperature ranges. In some implementations, the control circuit may be configured to select ones of the lasers to use for transmission based on the current temperature of the transmitter. In this manner, the control circuit can ensure that the lasers are not operated outside of their rated operating
20 temperature range.

Turning now to the figures, FIG. 9 shows an optical transmitter having a plurality of lasers for modulation and/or configuration of various characteristics of a light beam. The optical transmitter 900 includes a plurality of lasers 910, 912, and 914. Each of the lasers 910, 912, and 914 is configured to output a
25 respective light beam from the transmitter when selected by control circuit 920.

The optical transmitter 900 includes an optical multiplexer or an optical combiner to provide selected ones of the light beams to an optical fiber 942 connected to an optical data port 940. For example, in some implementations, the control circuit 920 is configured to enable/disable selected ones of the
30 plurality of lasers, and the transmitter 900 includes an optical combiner configured to combine light beams produced by enabled ones of the plurality of lasers and provide the combined beam to the optical fiber 942. In some other implementations, the transmitter 900 includes an optical multiplexer configured to provide light beams selected by the control circuit 920 to the optical fiber 942.

For ease of explanation, the optical transmitter is described as including an optical "multiplexer/combiner," which may be either an optical multiplexer or an optical combiner.

5 In some implementations, the lasers are turned on when selected and turned off when not selected. In some other implementations, all of the lasers emit light beams at the same time which are forwarded to an output or blocked by optical multiplexer/combiner 930. The optical multiplexer/combiner 930 forwards light beams from lasers selected by the control circuit 920 and may block light beams from other lasers.

10 Different ones of the lasers 910, 912, and 914 may have different temperature ranges at which the lasers will operate correctly. In some implementations, the control circuit 920 is configured to select ones of the lasers to use for transmission based on the current temperature of the transmitter as indicated by a temperature sensor 922. In this manner, the control circuit can
15 ensure that the lasers are not operated outside of their rated operating temperature range and that unusable lasers are turned off and do not consume power or generate interfering signals.

In some implementations, the control circuit 920 is configured to adjust an amplitude/intensity of the single light beam provided to the optical fiber 942 by
20 selecting different numbers of the lasers 910, 912, and 914 for transmission of light over the optical fiber at the same time. The control circuit 920 may be further configured to encode a data signal by modulating the amplitude/intensity of the single light beam provided to the optical fiber 942 to produce an amplitude modulated signal.

25 In some implementations, each of the lasers 910, 912, and 914 is configured to produce light of a respective frequency. The control circuit 920 may select different ones of the lasers to adjust a frequency of the single light beam provided to the optical fiber 942. The control circuit 920 may be further configured to encode a data signal by modulating a frequency of the single light
30 beam to produce a frequency modulated signal.

The example shown in FIG. 9 may be adapted for the selection of other types of optical communication circuits, such as optical modulators or waveguides. For instance, a control circuit (e.g., 920) may be configured to select ones of a plurality of optical modulators, which output respective light

beams. An optical multiplexer/combiner (e.g., 930) may be configured to forwards light beams from optical modulators that are selected by the control circuit and block light beams from other ones of the optical modulators.

FIG. 10 shows a process for communicating with a transmitter having multiple lasers. The temperature of optical circuits of a transmitter is monitored at block 1002. At block 1004, a laser is selected that has an operating temperature range spanning the current temperature of the optical circuits. At block 1006, the selected laser is enabled for communication and other ones of the lasers are disabled.

Circuits, apparatus, and methods are also disclosed for automated alignment of an optical fiber with communication circuits using multiple communication circuits. In some implementations, an optical communications device includes an optical data port for supporting an optical fiber in a fixed position. The optical communications device includes an array of communication circuits, each oriented to communicate optical signals at a respective position of a cross section of the optical fiber connected to the optical data port. In some implementations, the optical communications device includes a control circuit responsive to optical signals communicated on the optical fiber connected to the optical data port. The control circuit is configured to determine those of the optical communication circuits that are misaligned with the optical fiber and disable the optical communication circuits determined to be misaligned.

FIG. 11A illustrates a side cross sectional view of an optical data port having a plurality of communication circuits for communication over an optical fiber. The optical data port 1130 includes a structure 1132 having an opening 1134 shaped to receive an optical fiber 1110. The optical fiber 1110 includes a core 1114 surrounded by an outer jacket 1112. The outer jacket 1112 serves to protect the core 1114 and to increase reflectiveness at the surface of core, thereby reducing the loss of light during transmission.

The optical data port 1130 includes communication circuits (e.g., communication circuit 1122) arranged in an array of communication circuits 1120 and located at the back of the opening 1134. The communication circuits 320 are configured to transmit and/or receive optical data via the optical fiber. The communication circuits may include, for example, lasers, optical modulators, or optical waveguides to transmit optical signals and/or optical detectors to receive

optical signals. Those of the communication circuits 1120 that are aligned with the core 1114 may transmit/receive optical data at a respective position of the cross section of the opening. The optical data is communicated in a direction normal to the cross section of the optical fiber 1110.

5 In order to achieve the highest data rates and throughput in an optical communication system, the communication circuit must be aligned with the core of the optical fiber. FIG. 11B shows a cross section *B* of the optical fiber 1110 shown in FIG. 11A relative to a position of the single communication circuit 1122. As shown in this example, the single communication circuit 1122 is not aligned
10 with the core 1114 of the fiber. This misalignment is problematic for optical communications.

FIG. 11C shows the cross section *B* of the optical fiber 1110 relative to the array of communication circuits 1120. Each of the communication circuits 1120 is oriented at a respective position of the cross section. The array of
15 communication circuits 1120 provides a larger area for alignment with the core 1114 of the optical fiber in comparison to the single communication circuit 1122. For instance, although the communication circuit 1150 is not aligned with the core 1114, communication circuit 1152 is aligned with the core and may be used for communication.

20 Referring again to FIG. 11A, in some implementations, the optical data port includes a control circuit 1140 that is configured to determine those of the communication circuits that are aligned with the core and thereafter use the determined the communication circuits for communicating optical data. In some implementations, other ones of the communication circuits that are not aligned
25 with the core may be powered down to save power.

FIG. 12 shows a process for alignment of an optical fiber using an array of a plurality of communication circuits (e.g., lasers). An optical fiber is inserted into an optical data port at block 1202. At block 1204, communication is tested with each communication circuit in the array of communication circuits. Testing may
30 be performed using various processes. In some implementations, a first device may transmit optical data via the optical fiber to prompt a second device to provide a response. The response may be provided via the optical data line or an electronic communication network. In some implementations, the first device may send an electronic signal to the second device to prompt the second device

to send optical data to the first device via the optical fiber. Other testing mechanisms may also be used. At block 1206, communication circuits in the array that are aligned with the core of the optical fiber are determined. At block 1208, one or more of the communication circuits aligned with the core are
5 enabled, and the communication circuits of the array that are not aligned are disabled.

Apparatus and methods are also disclosed for orienting an optical fiber with an optical data port. In some implementations, an optical fiber is configured with a jacket having a non-circular cross section. The optical data port may also
10 have a non-circular cross section that is congruent to the jacket. The optical data port may be configured to engage the non-circular cross-section of the jacket only when it is aligned with the non-circular cross section of the optical data port.

FIG. 13 shows various non-circular optical fiber ends that may be used for
15 alignment of an optical fiber in accordance with one or more implementations. A first optical fiber has a core 1322 surrounded by a substantially circular jacket 1320. The jacket 1320 has a notch 1324 to give the jacket a non-circular cross section. A second optical fiber has a core 1332 surrounded by a substantially circular jacket 1330. The jacket 1330 includes a flat surface 1334, which gives
20 the jacket a non-circular cross section. A third optical fiber has a core 1342 surrounded by a substantially circular jacket 1340. The jacket 1340 includes two flat surfaces 1344 and 1346, which gives the jacket a non-circular cross section. A fourth optical fiber has a core 1352 surrounded by a jacket 1350 having an oval cross-section. The oval cross-section gives the jacket 1350 a non-circular
25 cross section. In some implementations, an optical fiber may include multiple cores. For instance, a fifth optical fiber has two cores 1362 and 1364 surrounded by jacket 1360. In this example the jacket 1360 has a rectangular cross section. The optical fibers may be modified to include jackets having other non-circular cross sections or having a different numbers of cores.

30 Apparatus, circuits, and methods are also disclosed for communication using optical differential signals. In some implementations, an optical communications system includes an optical transmitter configured to communicate using optical differential signals. The optical transmitter includes a first laser configured to transmit a first optical differential signal component of a

data signal received at an input terminal. The optical transmitter also includes a second laser configured to transmit a second optical differential signal that is a complement of the first optical differential signal component.

In some implementations, an optical communications system also
5 includes an optical receiver configured to receive the first and second optical signal components from the optical transmitter. The optical receiver is configured to retrieve the data signal based on the first and second optical signal components.

Turning back to the figures, FIG. 14 shows a system for communication
10 using optical differential signals. The optical communications system includes an optical transmitter 1410 and an optical receiver 1430 configured to communicate using optical differential signals. The optical transmitter 1410 includes a first laser 1412 configured to transmit a first optical differential signal component 1420 of a data signal received at an input terminal 1416. The optical
15 transmitter 1410 also includes a second laser 1414 configured to transmit a second optical differential signal 1422 that is a complement of the first optical differential signal component 1420. The signals are complementary in that when the first optical differential signal component encodes a logical '1,' the second optical differential signal component encodes a logical '0'. Conversely, when the
20 first optical differential signal component encodes a logical '0,' the second optical differential signal component encodes a logical '1'.

The optical receiver 1430 is configured to receive the first and second optical differential signal components 1420 and 1422 from the optical transmitter 1410. The optical receiver 1430 is configured to retrieve the original data signal
25 (received at input terminal 1416) based on the first and second optical signal components.

An example implementation of the optical receiver 1430 is shown by optical receiver 1450. In this example, the optical receiver 1450 includes a first photo-diode 1452 configured to receive the first optical differential signal
30 component and output a first voltage indicative of a light intensity of the first optical data signal component. The optical receiver 1450 also includes a second photo-diode 1454 configured to receive the second optical differential signal component and output a second voltage indicative of a light intensity of the second optical data signal component. The optical receiver 1450 includes a

demodulation circuit 1456 configured to demodulate the differential signal based on the first and second voltages to retrieve the original data signal (received at input terminal 1416). In this example, the demodulation circuit 1456 is implemented using a comparator circuit having a first input connected to the first
5 voltage and a second input connected to the second voltage.

In some implementations, the first and second optical signal components may be transmitted as respective light beams on respective optical fibers or on respective cores of an optical fiber. In some other implementations, the first and second optical differential signal components may be transmitted as respective
10 light beams on the same core of a single optical fiber. For instance, the first and second optical differential signal components may be transmitted as respective light beams having different respective frequencies. As the receiver 1450, the light beams may be separated (e.g., by a prism separator) and provided to respective photo-diode 1452 and 1454. In some other implementations, the first
15 and second optical differential signal components may be transmitted as respective light beams having different polarizations. At the receiver 1450, the first and second optical differential signal components may be separated using polarization filters and provided to the respective photo-diode 1452 and 1454.

The various implementations may be applicable to various applications using optical data communication. As one example, a programmable IC may include an input/output block configured to communicate data over an optical fiber. FIG. 15 shows an example programmable IC that may be configured for optical communication in accordance with one or more implementations. This example shows a type of programmable IC known as a Field-programmable-
20 gate-array (FPGA). FPGAs can include several different types of programmable logic blocks in the array. For example, FIG. 15 illustrates an FPGA architecture (1500) that includes a large number of different programmable tiles including multi-gigabit transceivers (MGTs) 1501, configurable logic blocks (CLBs) 1502, random access memory blocks (BRAMs) 1503, input/output blocks (IOBs) 1504,
25 configuration and clocking logic (CONFIG/CLOCKS) 1505, digital signal processing blocks (DSPs) 1506, specialized input/output blocks (I/O) 1507, for example, clock ports, and other programmable logic 1508 such as digital clock managers, analog-to-digital converters, system monitoring logic, and so forth. Some FPGAs also include dedicated processor blocks (PROC) 1510 and

internal and external reconfiguration ports (not shown). In some implementations, at least one of the IOBs 1504 is configured to communicate optical data in accordance with one or more of the above described implementations.

5 In some FPGAs, each programmable tile includes a programmable interconnect element (INT) 1511 having standardized connections to and from a corresponding interconnect element in each adjacent tile. Therefore, the programmable interconnect elements taken together implement the programmable interconnect structure for the illustrated FPGA. The
10 programmable interconnect element INT 1511 also includes the connections to and from the programmable logic element within the same tile, as shown by the examples included at the top of FIG. 15.

 For example, a CLB 1502 can include a configurable logic element CLE 1512 that can be programmed to implement user logic, plus a single
15 programmable interconnect element INT 1511. A BRAM 1503 can include a BRAM logic element (BRL) 1513 in addition to one or more programmable interconnect elements. Typically, the number of interconnect elements included in a tile depends on the height of the tile. In the pictured example, a BRAM tile has the same height as five CLBs, but other numbers (e.g., four) can also be
20 used. A DSP tile 1506 can include a DSP logic element (DSPL) 1514 in addition to an appropriate number of programmable interconnect elements. An IOB 1504 can include, for example, two instances of an input/output logic element (IOL) 1515 in addition to one instance of the programmable interconnect element INT 1511. As will be clear to those of skill in the art, the actual I/O bond pads
25 connected, for example, to the I/O logic element 1515, are manufactured using metal layered above the various illustrated logic blocks, and typically are not confined to the area of the input/output logic element 1515.

 In the pictured example, a columnar area near the center of the die (shown shaded in FIG. 15) is used for configuration, clock, and other control
30 logic. Horizontal areas 1509 extending from this column are used to distribute the clocks and configuration signals across the breadth of the FPGA.

 Some FPGAs utilizing the architecture illustrated in FIG. 15 include additional logic blocks that disrupt the regular columnar structure making up a large part of the FPGA. The additional logic blocks can be programmable blocks

and/or dedicated logic. For example, the processor block PROC 1510 shown in FIG. 15 spans several columns of CLBs and BRAMs.

Note that FIG. 15 is intended to illustrate only an exemplary FPGA architecture. The numbers of logic blocks in a column, the relative widths of the columns, the number and order of columns, the types of logic blocks included in the columns, the relative sizes of the logic blocks, and the interconnect/logic implementations included at the top of FIG. 15 are purely exemplary. For example, in an actual FPGA, more than one adjacent column of CLBs is typically included wherever the CLBs appear, to facilitate the efficient implementation of user logic.

The methods, circuits, and systems are thought to be applicable to a variety of systems and applications which utilize optical communication. Other aspects and features will be apparent to those skilled in the art from consideration of the specification. Though aspects and features may in some cases be described in individual figures, it will be appreciated that features from one figure can be combined with features of another figure even though the combination is not explicitly shown or explicitly described as a combination. The methods, circuits, and systems may be implemented as one or more processors configured to execute software, as an application specific integrated circuit (ASIC), or as a logic on a programmable logic device. It is intended that the specification and drawings be considered as examples only, with a true scope of the invention being indicated by the following claims.

An apparatus is disclosed. The apparatus comprises a package substrate, a first interposer mounted on the package substrate, a logic circuit and an optical interface circuit connected to the logic circuit via the first interposer. One of the optical interface circuit or the logic circuit is mounted on the first interpose. The optical interface circuit includes a driver circuit configured to receive electronic data signals from the logic circuit and an optical transmitter circuit coupled to the driver circuit and configured to output optical data signals encoding the electronic data signals.

Optionally, the apparatus further comprises a second interposer mounted on the package substrate. The other one of the optical interface circuit or the logic circuit may be mounted on the second interposer and the optical interface

circuit may be connected to the logic circuit via the first interposer and the second interposer.

Optionally, the optical interface circuit further includes a serializer circuit configured to receive parallel data from the logic circuit, serialize the parallel
5 data, and provide the serialized data to the driver circuit as the electronic data signals.

Optionally, the serializer circuit and the driver circuit may be connected by signal lines having lengths less than or equal to $1/8$ the wavelength of a highest frequency used by the serializer circuit to provide the serialized data to the driver
10 circuit.

Optionally, the apparatus further comprises a serializer circuit mounted on the first interposer and configured to receive parallel data from the logic circuit, serialize the parallel data, and provide the serialized data to the driver circuit, via the first and second interposers.

Optionally, the optical transmitter circuit includes a first set of optical
15 communication circuits configured and arranged to communicate optical data with a different setting of a first parameter and a selection circuit configured and arranged to select one of the first set of optical communication circuits for operation in response to a first control signal.

Optionally, the first set of optical communication circuits includes a
20 plurality of lasers.

Optionally, the first set of optical communication circuits includes a plurality of optical modulators.

Optionally, the apparatus further comprises a second set of optical
25 communication circuits configured and arranged to modulate an optical data signal output by the first set of optical communication circuits. Each of the second set of optical communication circuits may be configured to modulate a second parameter of the optical data signal by a respective amount. The selection circuit may be further configured and arranged to select one of the
30 second set of optical communication circuits for operation in response to a second control signal.

A method is disclosed. The method comprises mounting a logic circuit on a first interposer, forming an optical interface circuit on a second interposer by mounting an optical transmitter circuit on the second interposer, mounting a

driver circuit on the second interposer, and connecting the driver circuit via wiring on the second interposer. The method further comprises mounting the first interposer on a substrate, mounting the second interposer on the substrate and connecting the logic circuit and the optical interface circuit via the first interposer
5 and the second interposer.

Optionally, the forming of the optical interface circuit on a second interposer further includes mounting a serializer circuit on the second interposer, the serializer circuit being configured to receive parallel data from the logic circuit, serialize the parallel data, and provide the serialized data to the driver
10 circuit.

Optionally, the method further comprises connecting the serializer circuit and the driver circuit using signal lines having lengths less than or equal to $1/8$ the wavelength of a highest frequency used by the serializer circuit to provide the serialized data to the driver circuit.

Optionally, the method further comprises mounting a serializer circuit on the first interposer, wherein the serializer circuit is configured to receive parallel data from the logic circuit, serialize the parallel data, and provide the serialized data to the driver circuit, via the first and second interposers.
15

An apparatus is disclosed. The apparatus comprises an optical serializer including a plurality of optical modulators, each configured and arranged to receive a respective bit of a parallel N-bit data bus, the respective bit having a first bit period, and output a respective optical pulse representing a value of the respective bit and having a duration less than the first bit period, wherein N is greater than or equal to 2. For each of the plurality of optical modulators, a
20 respective optical delay line may be configured and arranged to delay the respective optical pulses of the optical modulator by a respective length of time unique to the optical modulator to produce a respective optical output signal and an optical combiner may be configured and arranged to combine the respective optical output signals produced by the optical delay line into a single optical
25 beam.
30

Optionally, the respective optical pulse output to each of the plurality of optical modulators may have a first duration equal to the first bit period divided by N.

Optionally, the optical delay line is further configured and arranged to delay output of each of the plurality of optical modulators by an amount of time equal to a respective multiple of the first duration.

Optionally, for the output of one of the plurality of optical modulators, the
5 respective multiple is equal to zero.

Optionally, the apparatus further comprises an optical fiber having a first end connected to an output of the optical combiner and an optical deserializer connected to a second end of the optical fiber. The optical deserializer may be configured and arranged to receive the single optical beam via the optical fiber;,
10 separate the optical output signals from the single optical beam and provide the optical output signals as respective bits of a parallel N-bit data bus.

A method is disclosed. For each bit of parallel N-bit data bus transmitted in a first bit period, using a respective optical modulator to provide a respective optical pulse having a duration less than the first bit period, wherein N is greater
15 than or equal to 2, the method may delay each of the respective optical pulses by a respective length of time unique to the optical modulator to produce a respective optical output signal and combine the respective optical output signals into a single optical beam.

Optionally, the respective optical pulse has a first duration equal to the
20 first bit period divided by N and the delaying of each of the respective optical pulses includes delaying each of the respective optical pulses by an amount of time equal to a respective multiple of the first duration.

An optical transmitter is disclosed. The optical transmitter comprises an optical data port configured to engage an optical fiber, a plurality of optical
25 communication circuits coupled to the optical data port and configured and arranged to transmit respective optical signals over the optical fiber via the optical data port when selected and a control circuit configured and arranged to receive an input data signal and encode the input data signal for transmission over the optical fiber by selecting one or more of the plurality of optical
30 communication circuits at a time according to one of a frequency modulation encoding algorithm or an amplitude modulation encoding algorithm.

Optionally, the optical transmitter further comprises a combiner configured to combine light emitted by the plurality of optical communication circuits into a single light beam.

Optionally, the control circuit is further configured and arranged to enable the selected one or more of the plurality of optical communication circuits and disable other ones of the plurality of optical communication circuits.

Optionally, the plurality of optical communication circuits includes a
5 plurality of lasers. Each of the plurality of lasers may be configured to produce light having a respective frequency and the control circuit may be further configured and arranged to select ones of the plurality of lasers to modulate a frequency of the single light beam.

Optionally, the plurality of optical communication circuits may include a
10 plurality of lasers. The plurality of lasers may be configured to produce light of a same frequency and the single light beam may be an amplitude modulated signal having an amplitude based on a number of the plurality of lasers that are selected by the control circuit for optical communication.

Optionally, the optical transmitter may further comprise an optical
15 multiplexer configured to receive a respective light beam from each of the plurality of optical communication circuits and output the light beams received from the one or more of the plurality of optical communication circuits selected by the control circuit.

An optical transmitter is disclosed. The optical transmitter comprises a
20 plurality of lasers configured and arranged to transmit respective optical signals via an optical data port, each of the plurality of lasers having a respective operating temperature range and a control circuit configured and arranged to select, as a function of one or more operating characteristics, one of the plurality of lasers at a time to transmit the respective optical signal via the optical data
25 port.

Optionally, the optical transmitter further comprises a temperature sensor coupled to the control circuit, the temperature sensor configured and arranged to measure a temperature of the optical transmitter. The control circuit may be configured and arranged to select the one of the plurality of lasers at a time as a
30 function of the temperature of the optical transmitter.

Optionally, the control circuit is further configured and arranged to enable a selected one of the plurality of lasers and disable other ones of the plurality of lasers.

An optical communication device is disclosed. The optical communication device comprises an optical data port configured and arranged to support an optical fiber in a fixed position, a plurality of optical communication circuits, each oriented to communicate optical signals at a respective position of a cross section of the optical fiber connected to the optical data port and a control circuit, responsive to optical signals communicated on the optical fiber connected to the optical data port, configured and arranged to determine ones of the plurality of optical communication circuits that are misaligned with the optical fiber and disable the determined ones of the plurality of optical communication circuits.

Optionally, the plurality of optical communication circuits includes a plurality of lasers, each oriented to transmit optical signals at a respective position of the cross section of the optical fiber in a direction that is normal to the cross section of the optical fiber.

Optionally, the plurality of optical communication circuits includes a plurality of optical detectors, each oriented to receive optical signals at a respective position of the cross section of the optical fiber.

An optical communication device is disclosed. The optical communication device comprises an optical data port configured and arranged to support an optical fiber in a fixed position. The optical fiber has a jacket with a non-circular cross section, the optical data port has a non-circular cross section, and the optical data port may be further arranged to engage the non-circular cross section of the jacket only when it is aligned with the non-circular cross section of the optical data port.

Optionally, the non-circular cross section of the optical fiber and the non-circular cross section of the optical data port each include at least one notch.

An optical communications system is disclosed. The optical communications system comprises an optical transmitter including an input terminal, a first laser coupled to the input terminal and configured to transmit a first optical differential signal component of a data signal received at the input terminal and a second laser coupled to the input terminal and configured to transmit a second optical differential signal component that may be a complement of the first optical differential signal component.

The optical communications system may further comprise an optical receiver including a first photo-diode configured and arranged to receive the first

optical differential signal component and output a first voltage indicative of a light intensity of the first optical differential signal component, a second photo-diode configured to receive the second optical differential signal component and output a second voltage indicative of a light intensity of the second optical differential
5 signal component and a demodulation circuit configured to demodulate the differential signal components based on the first and second voltages to retrieve the data signal.

Optionally, the demodulation circuit is a comparator circuit having a first input connected to the first voltage and a second input connected to the second
10 voltage.

Optionally, the optical transmitter is configured and arranged to transmit the first and second optical differential signal components on respective optical fibers.

Optionally, the system further comprises a first polarization filter
15 configured to polarize the first optical differential signal component and a second polarization filter configured to polarize the second optical differential signal component. The polarization of the first optical differential signal component may be orthogonal to the polarization of the second optical differential signal component and the optical transmitter may be configured and arranged to
20 transmit the first and second optical differential signal components on a single optical fiber.

Optionally, the first and second lasers are different frequencies and the optical transmitter may be configured and arranged to transmit the first and second optical differential signal components on a single optical fiber.

25

CLAIMS

What is claimed is:

1. An apparatus comprising,
a package substrate;
5 a first interposer mounted on the package substrate;
a logic circuit;
an optical interface circuit connected to the logic circuit via the first interposer; and
wherein:
10 one of the optical interface circuit or the logic circuit is mounted on the first interposer; and
the optical interface circuit includes:
a driver circuit configured to receive electronic data signals from the logic circuit; and
15 an optical transmitter circuit coupled to the driver circuit and configured to output optical data signals encoding the electronic data signals.
2. The apparatus of claim 1, further comprising:
20 a second interposer mounted on the package substrate;
the other one of the optical interface circuit or the logic circuit is mounted on the second interposer; and
the optical interface circuit is connected to the logic circuit via the first interposer and the second interposer.
- 25 3. The apparatus of claim 2, wherein:
the optical interface circuit further includes a serializer circuit configured to receive parallel data from the logic circuit, serialize the parallel data, and provide the serialized data to the driver circuit as the electronic data signals.
- 30 4. The apparatus of claim 3, wherein the serializer circuit and the driver circuit are connected by signal lines having lengths less than or equal to $1/8$ the wavelength of a highest frequency used by the serializer circuit to provide the serialized data to the driver circuit.

5. The apparatus of claim 2, further comprising:
a serializer circuit mounted on the first interposer and configured to receive parallel data from the logic circuit, serialize the parallel data, and provide
5 the serialized data to the driver circuit, via the first and second interposers.
6. The apparatus of claim 1, wherein the optical transmitter circuit includes:
a first set of optical communication circuits configured and arranged to communicate optical data with a different setting of a first parameter; and
10 a selection circuit configured and arranged to select one of the first set of optical communication circuits for operation in response to a first control signal.
7. The apparatus of claim 6, wherein the first set of optical communication circuits includes a plurality of lasers.
15
8. The apparatus of claim 6, wherein the first set of optical communication circuits includes a plurality of optical modulators.
9. The apparatus of claim 6, further comprising:
20 a second set of optical communication circuits configured and arranged to modulate an optical data signal output by the first set of optical communication circuits, each of the second set of optical communication circuits configured to modulate a second parameter of the optical data signal by a respective amount; and
25 wherein the selection circuit is further configured and arranged to select one of the second set of optical communication circuits for operation in response to a second control signal.
10. The apparatus of claim 1, wherein the optical interface circuit comprises
30 an optical serializer, including:
a plurality of optical modulators, each configured and arranged to receive a respective bit of a parallel N-bit data bus, the respective bit having a first bit period, and output a respective optical pulse representing

a value of the respective bit and having a duration less than the first bit period, wherein N is greater than or equal to 2;

5 for each of the plurality of optical modulators, a respective optical delay line configured and arranged to delay the respective optical pulses of the optical modulator by a respective length of time unique to the optical modulator to produce a respective optical output signal; and an optical combiner configured and arranged to combine the respective optical output signals produced by the optical delay line into a single optical beam.

10 11. The apparatus of claim 10, wherein the respective optical pulse output to each of the plurality of optical modulators has a first duration equal to the first bit period divided by N.

12. A method, comprising
15 mounting a logic circuit on a first interposer;
forming an optical interface circuit on a second interposer by mounting an optical transmitter circuit on the second interposer, mounting a driver circuit on the second interposer, and connecting the driver circuit via wiring on the second interposer;
20 mounting the first interposer on a substrate;
mounting the second interposer on the substrate; and
connecting the logic circuit and the optical interface circuit via the first interposer and the second interposer.

25 13. The method of claim 12, wherein the forming of the optical interface circuit on a second interposer further includes mounting a serializer circuit on the second interposer, the serializer circuit being configured to receive parallel data from the logic circuit, serialize the parallel data, and provide the serialized data to the driver circuit.

30 14. The method of claim 13, further comprising:
connecting the serializer circuit and the driver circuit using signal lines having lengths less than or equal to $1/8$ the wavelength of a highest frequency used by the serializer circuit to provide the serialized data to the driver circuit.

15. The method of claim 12, further comprising:
mounting a serializer circuit on the first interposer, wherein the serializer
circuit is configured to receive parallel data from the logic circuit, serialize the
5 parallel data, and provide the serialized data to the driver circuit, via the first and
second interposers.

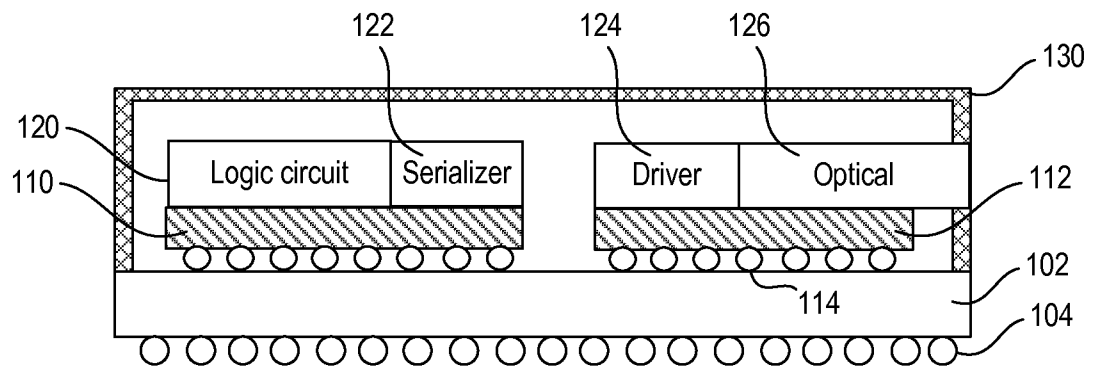


FIG. 1

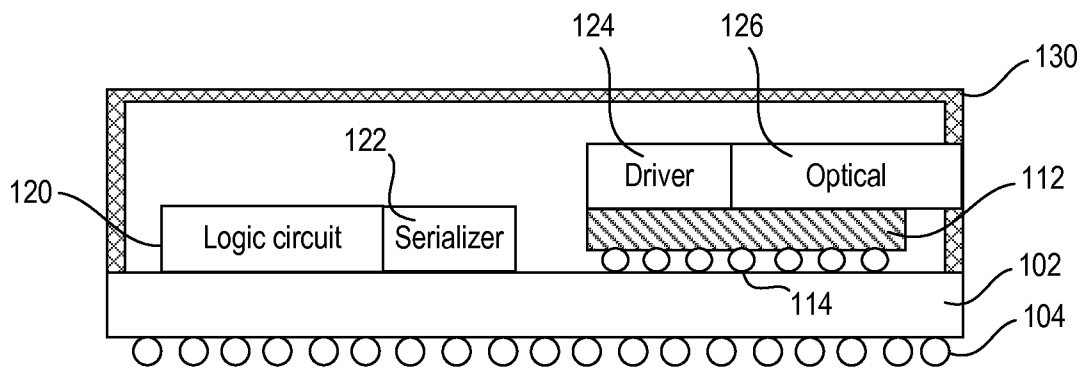


FIG. 2

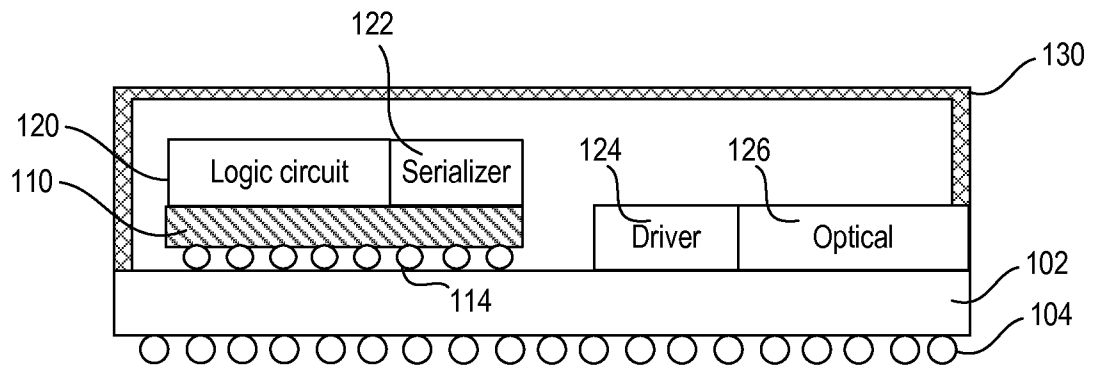


FIG. 3

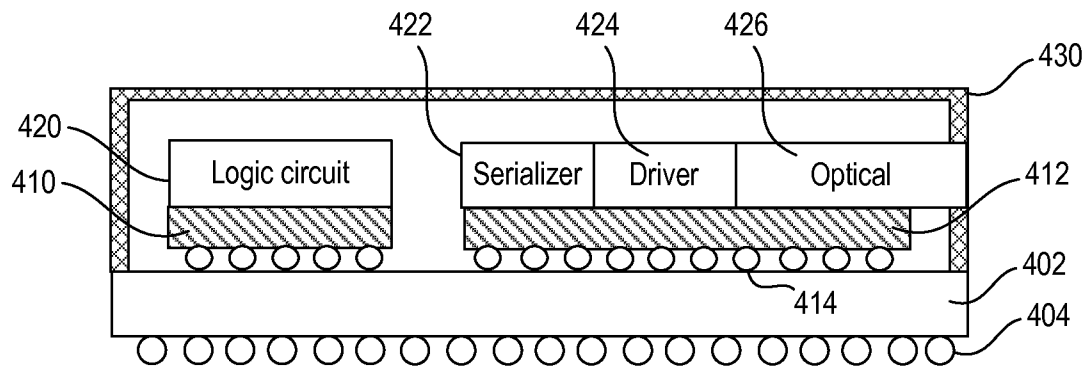


FIG. 4

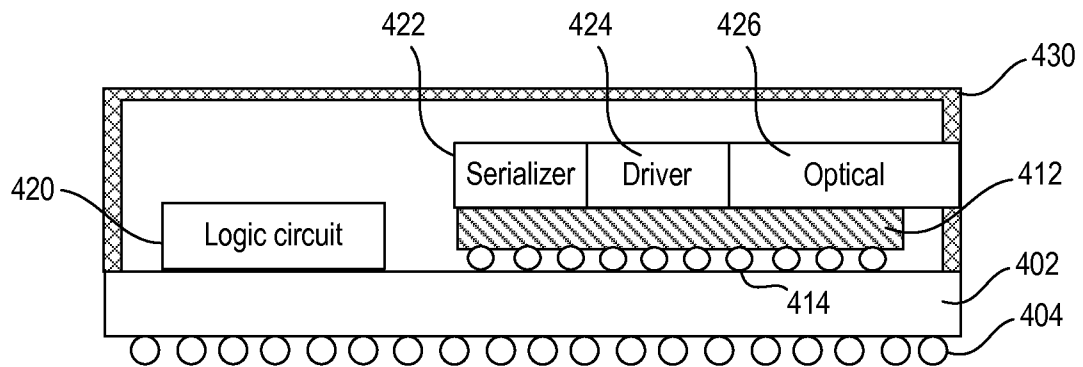


FIG. 5

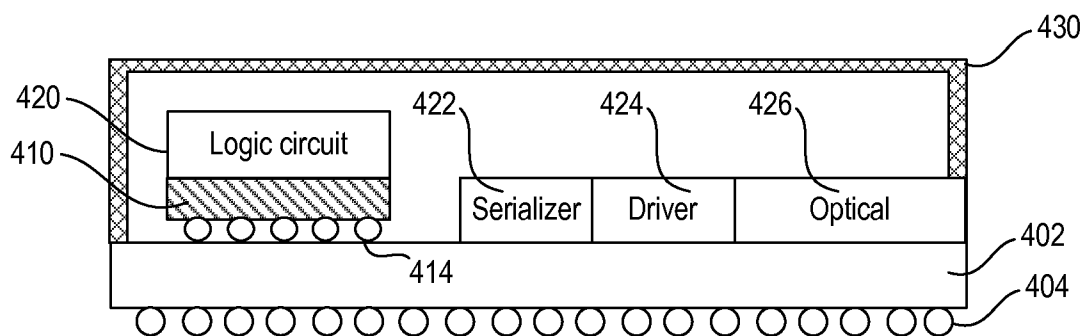


FIG. 6

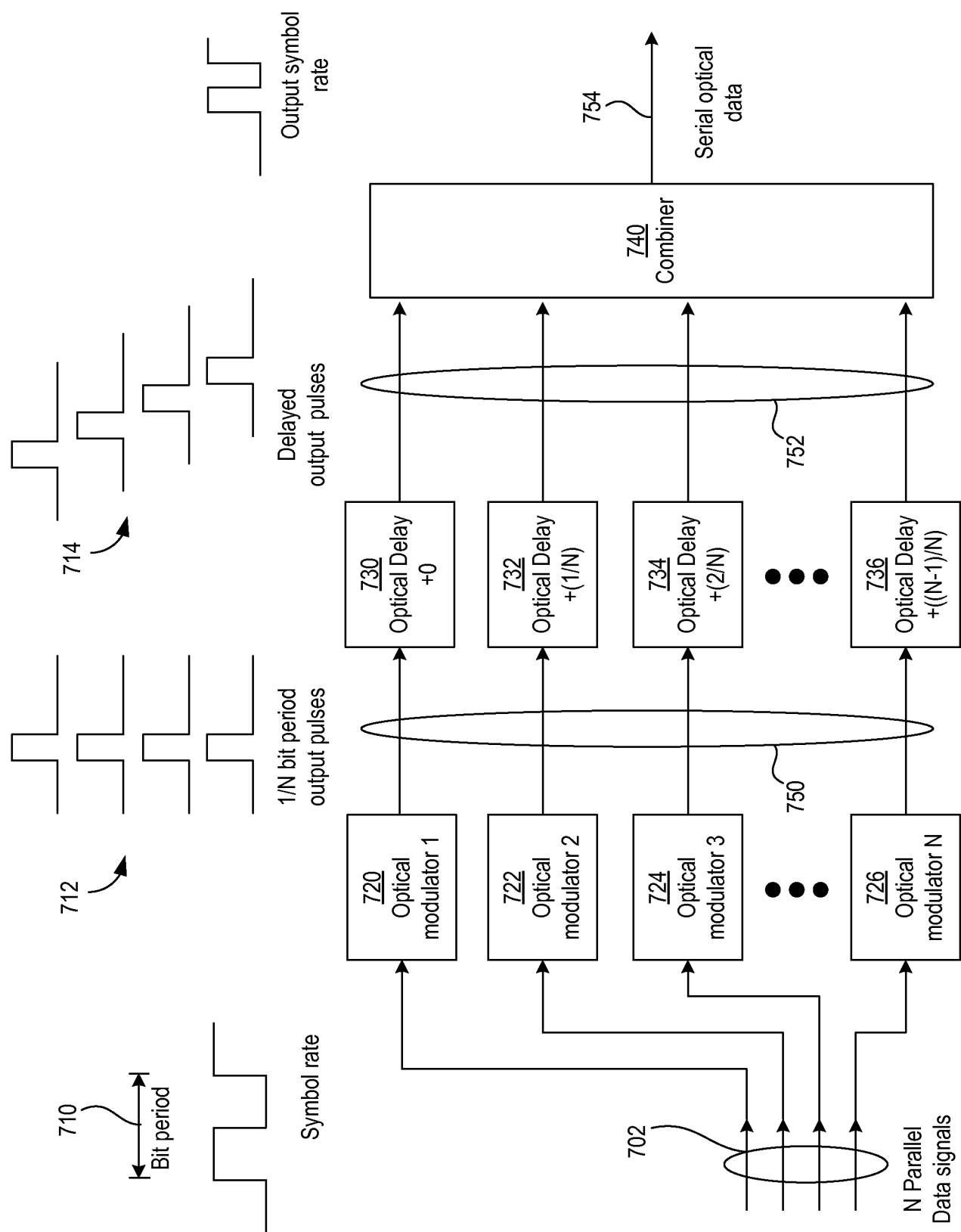


FIG. 7

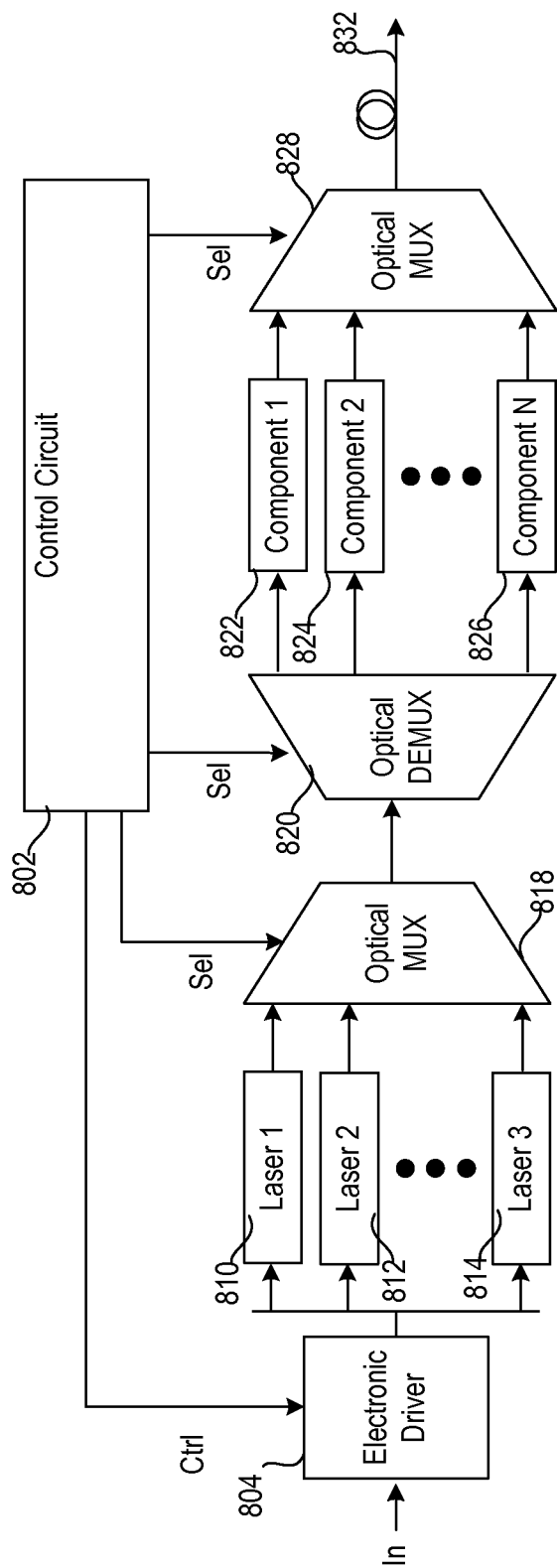


FIG. 8

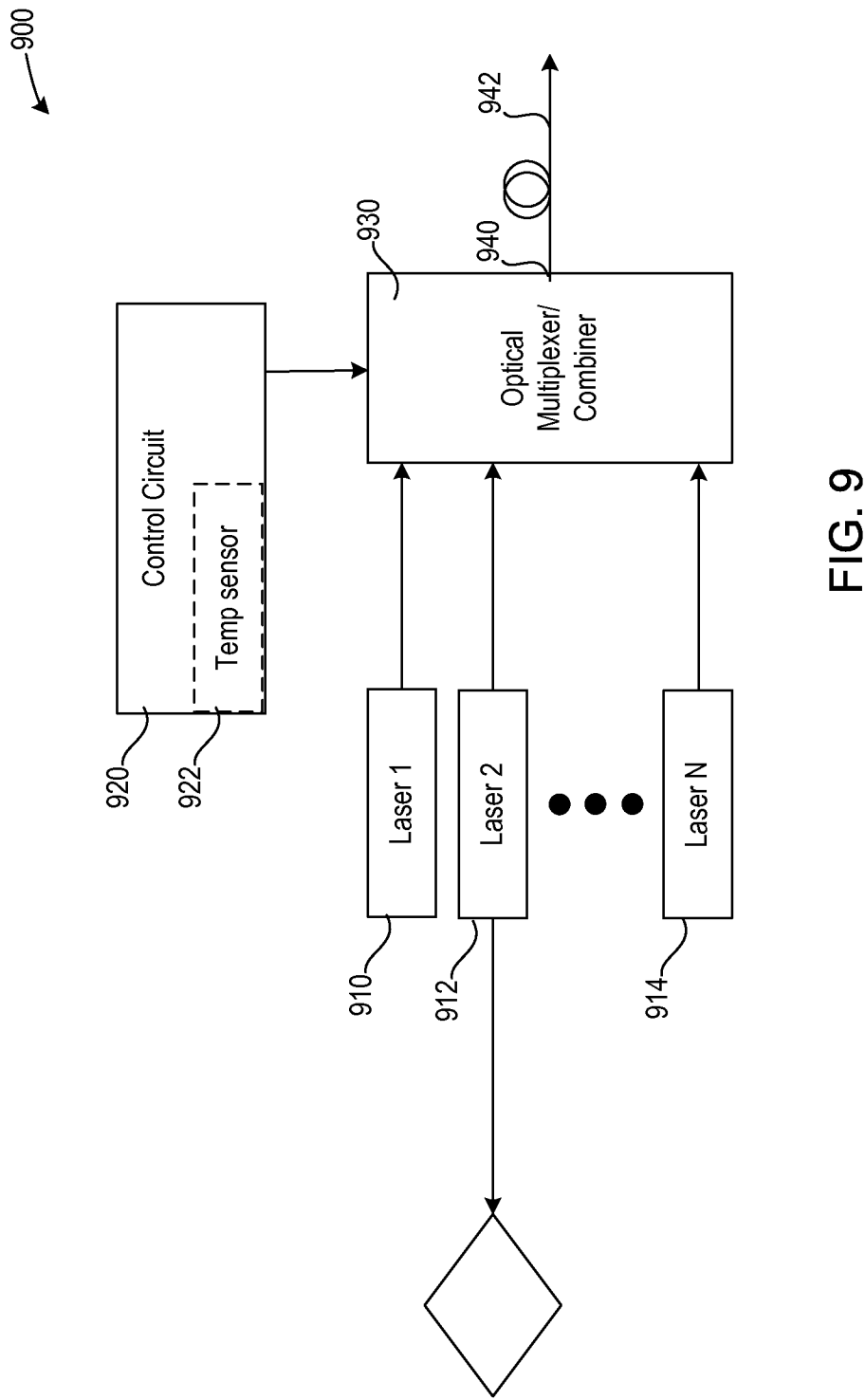


FIG. 9

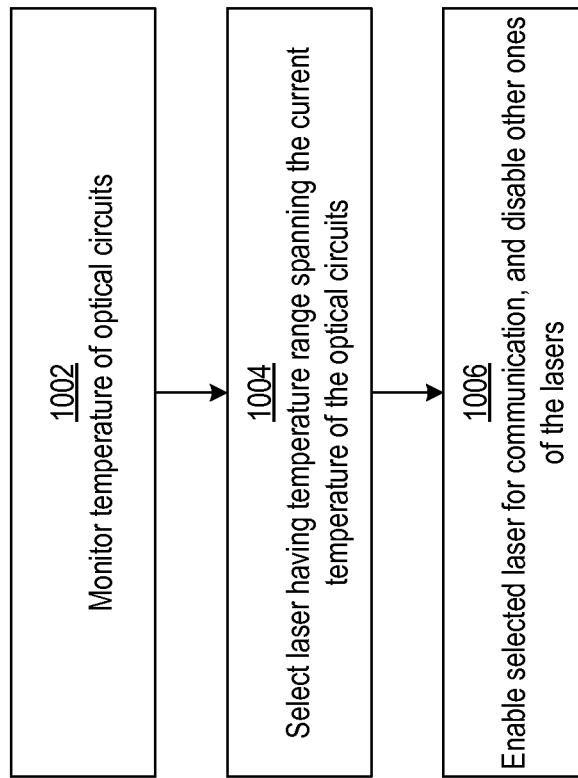


FIG. 10

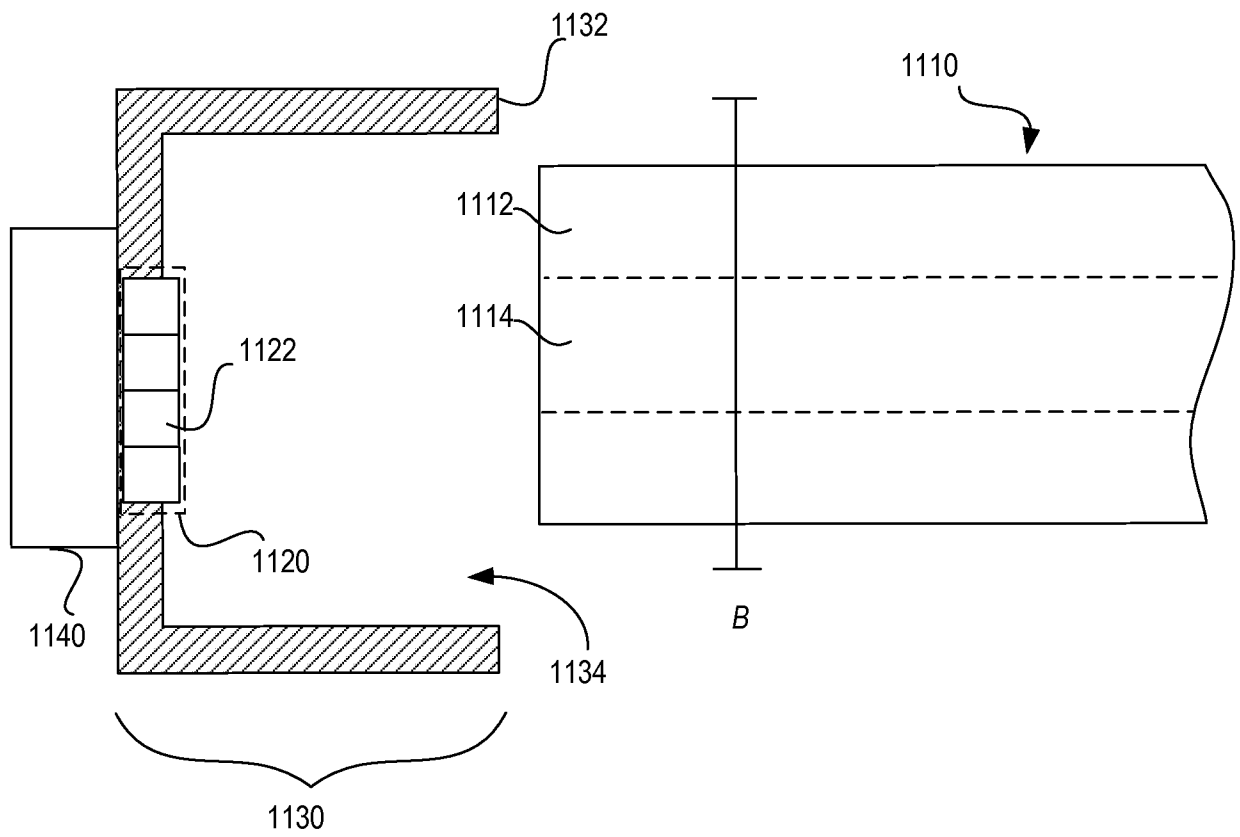


FIG. 11A

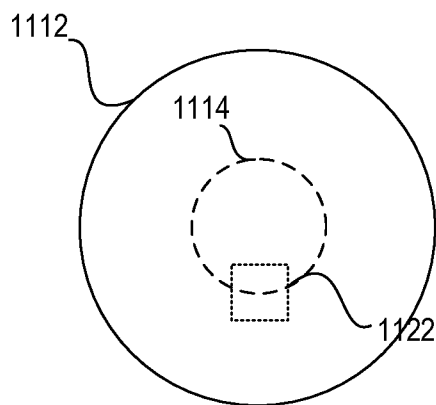


FIG. 11B

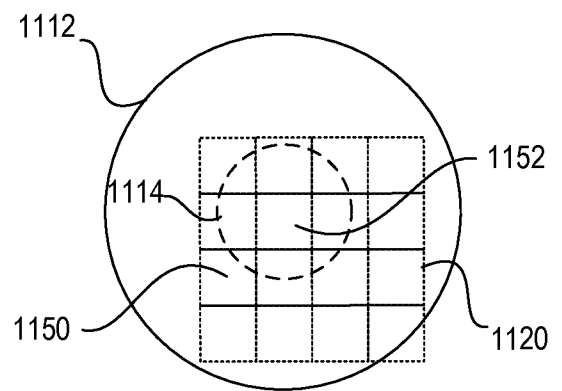


FIG. 11C

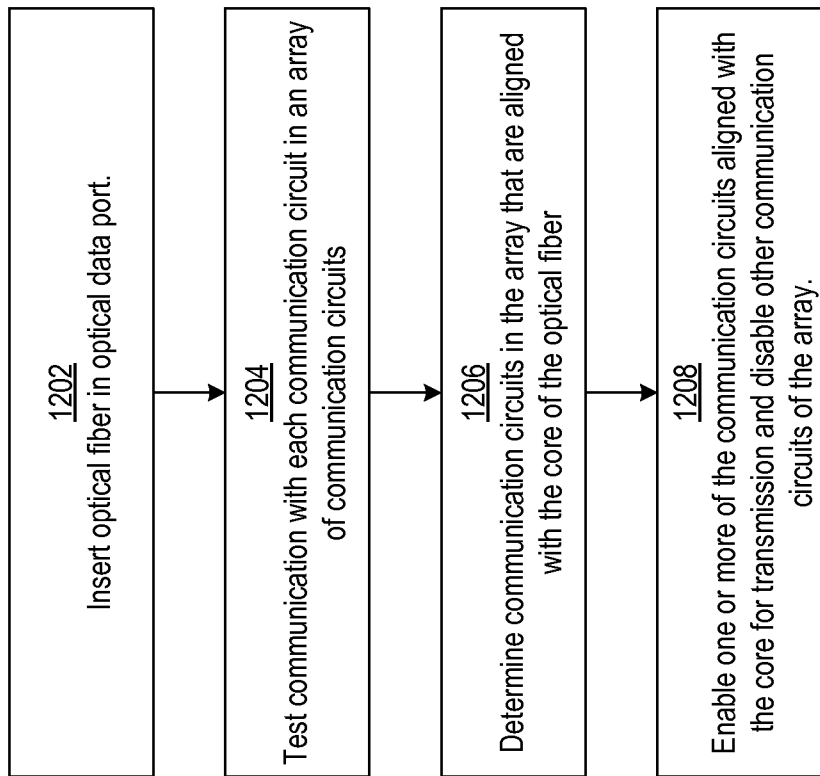


FIG. 12

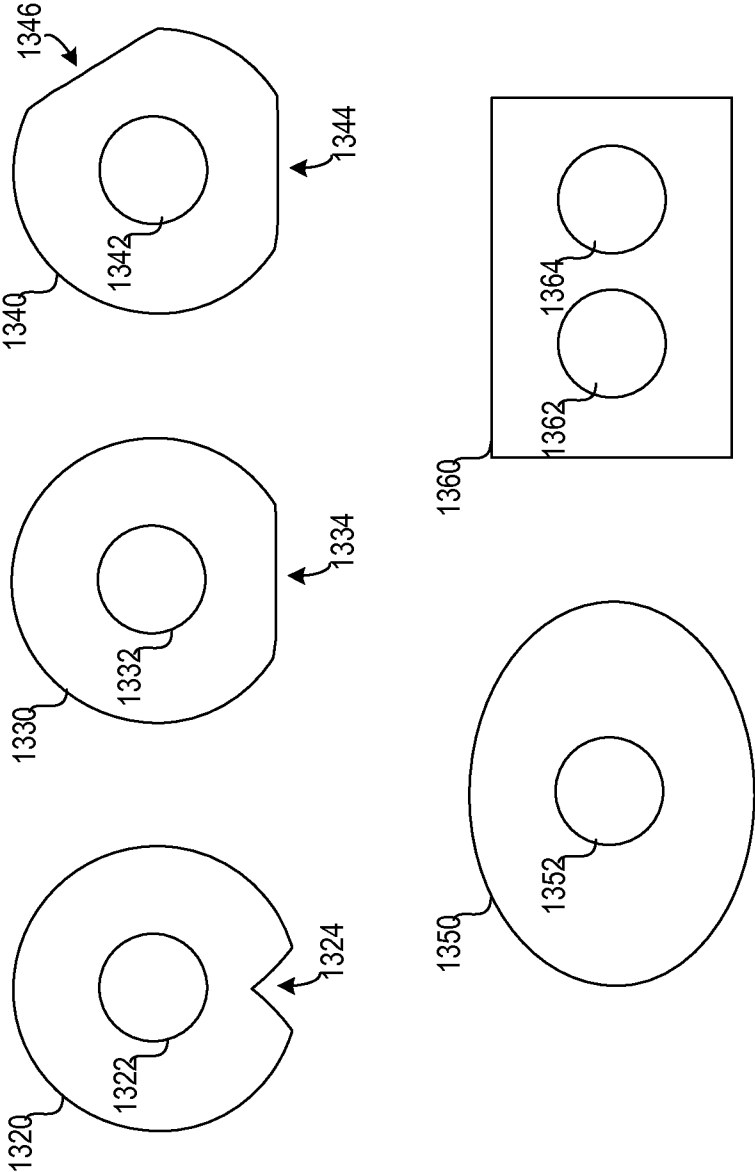


FIG. 13

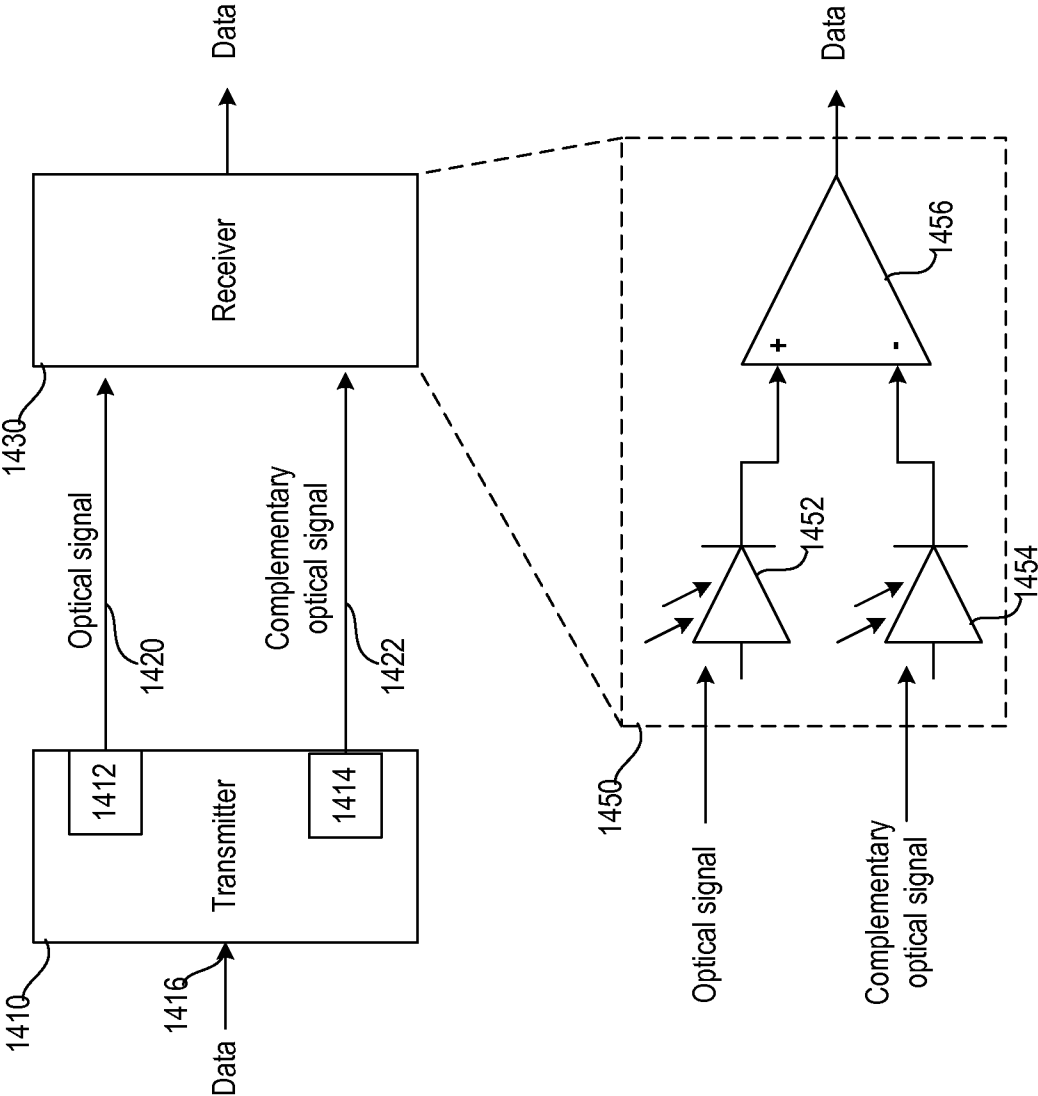


FIG. 14

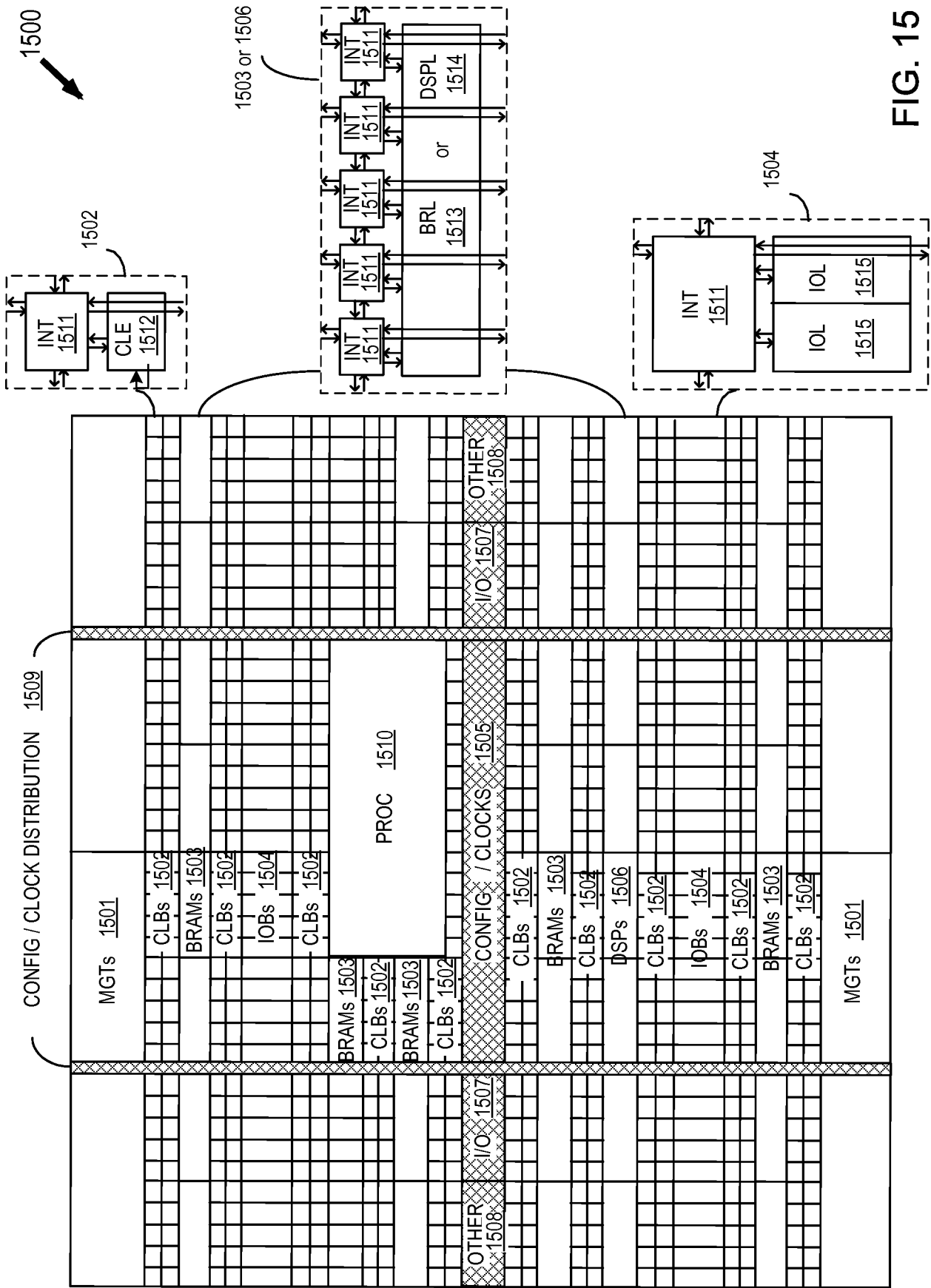


FIG. 15

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2015/033598

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04B10/50 H04B10/80
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H04B H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EP0-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	MASAO TOKUNARI ET AL: "High-bandwidth optical MCM: FPGA with optical I/O on waveguide-integrated SLC", CPMT SYMPOSIUM JAPAN, 2010 IEEE, IEEE, PISCATAWAY, NJ, USA, 24 August 2010 (2010-08-24), pages 1-4, XP031843784, ISBN: 978-1-4244-7593-3 figures 1, 4 page 2, column 1, line 11 - line 12 -----	1-15
Y	US 2006/043585 A1 (SUKEGAWA SHUNICHI [JP] ET AL) 2 March 2006 (2006-03-02) figure 1 paragraph [0007] ----- -/--	1-15



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

5 August 2015

Date of mailing of the international search report

12/08/2015

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

Ganzmann, Anna

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2015/033598

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2006/269294 A1 (KIKUCHI NOBUHIKO [JP]) 30 November 2006 (2006-11-30) figure 13 -----	1-15
A	US 8 546 955 B1 (WU EPHREM C [US]) 1 October 2013 (2013-10-01) figures 6-1 -----	1-15
A	US 6 963 123 B2 (NAGASE TORU [JP] ET AL) 8 November 2005 (2005-11-08) figure 3A -----	1-15
A	ISHII Y ET AL: "Demonstration of on-PCB optical interconnection using surface-mount package and polymer waveguide", 2003 PROCEEDINGS 53RD. ELECTRONIC COMPONENTS AND TECHNOLOGY CONFERENCE. (ECTC). NEW ORLEANS, LA, MAY 27 - 30, 2003; [PROCEEDINGS OF THE ELECTRONIC COMPONENTS AND TECHNOLOGY CONFERENCE], NEW YORK, NY : IEEE, US, vol. CONF. 53, 27 May 2003 (2003-05-27), pages 1147-1152, XP010648067, DOI: 10.1109/ECTC.2003.1216436 ISBN: 978-0-7803-7991-6 figure 1 -----	1-15

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2015/033598

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2006043585 A1	02-03-2006	JP 4752369 B2	17-08-2011
		JP 2006093659 A	06-04-2006
		KR 20060050604 A	19-05-2006
		TW 1278096 B	01-04-2007
		US 2006043585 A1	02-03-2006
		US 2008150834 A1	26-06-2008
		US 2008284004 A1	20-11-2008
		US 2008290508 A1	27-11-2008
US 2006269294 A1	30-11-2006	CN 1874199 A	06-12-2006
		JP 4648093 B2	09-03-2011
		JP 2006339760 A	14-12-2006
		US 2006269294 A1	30-11-2006
US 8546955 B1	01-10-2013	NONE	
US 6963123 B2	08-11-2005	JP 4159778 B2	01-10-2008
		JP 2003198034 A	11-07-2003
		US 2003122228 A1	03-07-2003
		US 2003197257 A1	23-10-2003