

SYSTEM FOR PULSED LASER OPTICAL DATA TRANSMISSION WITH RECEIVER RECOVERABLE CLOCK

CROSS REFERENCE TO RELATED APPLICATIONS

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This application claims the benefit of priority of U.S. Provisional patent application No. 63/142,684 filed January 28, 2021, which is incorporated herein by reference in its entirety.

FIELD

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Embodiments of various systems disclosed herein relate in general to signal transmission and more specifically to systems for transmission of high data rate optical signals.

BACKGROUND

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Coherent and non-coherent optical transceivers for high data rate transmissions such as 400Gbps and beyond generally utilize digital signal processors (DSPs). The DSPs provide one or more of pre or post compensation of chromatic dispersion, other channel impairments, multiplexing and demultiplexing, implementation of high-level modulation formats and/or error correction to enable such high rates such as when using PAM4 (or other modulation).

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The required DSPs have high power consumption – typically 8W for a DSP in a system with a data rate of 400Gbps, or higher power consumption for greater data rates, thus increasing the power requirements of high bitrate systems. Further, the multiplexing of multiple data channels and the other signal processing on the electrical signals introduces latency into the signal transmission. Still further, DSPs have a limited maximum throughput due to the constraints of electrical processing. It would be therefore be desirable to provide transmission systems featuring high data rates without the need for DSPs to thereby reduce the power consumption and latency and overcome the electrical bandwidth bottleneck.

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SUMMARY

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Embodiments disclosed herein relate to systems, devices and methods that enable high data rate optical signals with reduced power consumption and reduced latency. The systems as described herein make use of all-optical transmitters and receivers such that no DSP is

required, thereby reducing the power requirements and latency of the system for sending equivalent data rates. An all-optical transmitter receiver arrangement also reduces computational complexity (such as needed by a DSP). In some embodiments, the all-optical transmitters and receivers are provided as integrated circuits (ICs) on shared semiconductor
5 substrates to further reduce power and size requirements.

In order to provide an all-optical receiver, the clock (local oscillator) used in the transmitted modulated signal is needed at the receiver. A presently disclosed system uses a modulated pulsed laser for data transmission, utilizing the periodic pulses as a clock. The clock based on the pulsed laser is transmitted along with the data signal and recovered by the receiver
10 to thereby serve as the required local oscillator. In some embodiments, orthogonal transverse modes are used, one carrying the data and the other carrying the clock. In some embodiments, separate data and clock channels are transmitted to the receiver. To enable all-optical demodulation based on the received clock, the receiver advantageously includes a saturable absorber (SA) configured to transmit received data pulses when saturated by clock pulses to
15 thereby recover the transmitted data signals.

In some embodiments, optical time division multiplexing (OTDM) is provided for transmission of multiple data channels. Use of optical multiplexing reduces latency and complexity compared with electrical multiplexing such as in DSPs. In some embodiments, systems as disclosed herein may be duplicated or may be provided with integrated WDM
20 systems for transmission of greater numbers of channels per fiber optic cable. In some embodiments, single mode fiber optic cable is used with unidirectional operation. In some embodiments, full duplex fiber optic cable is used with bidirectional operation. Further, dispersion management is also handled optically in the receiver to compensate for dispersion in transmission and for dispersion that may be caused by the saturable absorbers. As above,
25 use of optical dispersion management reduces the computational complexity of the solution.

In some embodiments, a system comprises: an optical transmitter that includes a pulsed laser for outputting a pulsed laser signal, wherein the optical transmitter is configured to modulate the pulsed laser signal based on a plurality of data signals to form a plurality of modulated optical data signals, to optically time division multiplex the plurality of modulated
30 optical data signals to obtain a multiplexed optical data signal, and to transmit the multiplexed optical data signal together with an optical clock signal derived from the pulsed laser signal; and an optical receiver that includes a clock recovery branch and a data branch, wherein the clock recovery branch is configured to recover and phase-shift the optical clock signal into a plurality of phase-shifted recovered optical clock signals, wherein the data branch includes a

plurality of SAs, and wherein each SA is in optical communication with one of the plurality of phase-shifted recovered optical clock signals and is configured to receive the multiplexed optical data signal and to transmit one of the modulated optical data signals received in the multiplexed optical data signal according to the one of the plurality of phase-shifted recovered optical clock signals.

In some embodiments, the optical clock signal and the multiplexed optical data signal are transmitted by the optical transmitter in orthogonal transverse modes over a single mode fiber optic cable. In some embodiments, the optical clock signal and multiplexed optical data signal are each transmitted by the optical transmitter over a separate cable in a full-duplex fiber optic cable. In some embodiments, wherein a clock pulse from one of the plurality of phase-shifted recovered optical clock signals saturates a related SA to thereby cause the SA to release a pulse from one of the plurality of modulated optical data signals.

In some embodiments, the clock recovery branch includes a splitter and a phase-shifter for extracting the optical clock signal into a plurality of phase-shifted extracted optical clock signals. In some embodiments, the optical receiver further includes one or more dispersion managers configured for dispersion correction of the plurality of modulated optical data signals and the plurality of phase-shifted extracted optical clock signals. In some embodiments, the optical receiver further comprises output components configured for extracting the plurality of data signals from each of the plurality of modulated optical data signals.

In some embodiments, the pulsed laser is a selected from the group consisting of a bulk laser, a quantum well laser, a quantum dot laser, a semiconductor mode-locked laser and a mode-locked integrated external-cavity surface emitting laser. In some embodiments, the pulsed laser has a pulse repetition rate between 5 GHz to 100 GHz. In some embodiments, the optical receiver includes an optical amplifier (OA). In some embodiments, the OA is a quantum dot semiconductor optical amplifier.

In some embodiments, the modulation is one of pulsed amplitude modulation (PAM) or quadrature amplitude modulation (QAM). In some embodiments, the plurality of data signals includes between 2-16 data signals per wavelength. In some embodiments, the plurality of data signals are digital signals and/or analog signals.

In some embodiments, a transmission system comprises a first transceiver and a second transceiver, wherein each of the first and second transceivers includes an optical transmitter, an optical receiver and a controller, wherein each optical transmitter is configured to modulate the pulsed laser signal based on a plurality of data signals to form a plurality of modulated optical data signals, to optically time division multiplex the plurality of modulated optical data

signals to obtain a multiplexed optical data signal, and to transmit the multiplexed optical data signal together with an optical clock signal derived from the pulsed laser signal, and wherein each optical receiver includes a clock recovery branch and a data branch, wherein the clock recovery branch is configured to recover and phase-shift the optical clock signal into a plurality of phase-shifted recovered optical clock signals, wherein the data branch includes a plurality of SAs, and wherein each SA is in optical communication with one of the plurality of phase-shifted recovered optical clock signals and is configured to receive the multiplexed optical data signal and to transmit one of the modulated optical data signals received in the multiplexed optical data signal according to the one of the plurality of phase-shifted recovered optical clock signals.

In some embodiments, each controller is configured for monitoring transceiver performance and for performing adjustment of the transmitter and receiver in order to optimize the transceiver performance. In some embodiments, the monitoring includes monitoring of one or more of bit error rate, data throughput, frame loss, or jitter. In some embodiments, each transceiver is formed on a common semiconductor substrate as an IC.

This summary is provided to introduce a selection of concepts in a simplified form that are further described below in the detailed description. This summary is not intended to identify key features or essential features of the claimed subject matter, nor is it intended to be used to limit the scope of the claimed subject matter.

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BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments disclosed herein are described, by way of example only, with reference to the following accompanying drawings, wherein:

FIG. 1A shows an optical system for data transmission over single mode fiber according to some embodiments;

FIG. 1B shows a transmitter for use with a single mode fiber according to some embodiments;

FIG. 1C shows illustrative signal amplitude graphs of the of the optical signals within the transmitter according to some embodiments;

FIG. 1D shows a receiver for use with a single mode fiber according to some embodiments;

FIG. 1E shows illustrative signal amplitude graphs of the optical signals within the receiver according to some embodiments;

FIGS. 1F and 1G show multiple optical transmission systems according to some embodiments;

FIG. 2A shows an optical system for data transmission over full duplex fiber according to some embodiments;

5 FIG. 2B shows a transmitter for use with a full duplex fiber according to some embodiments;

FIG. 2C shows a coupling assembly for use with a full duplex fiber according to some embodiments;

10 FIG. 2D shows a receiver for use with a full duplex fiber according to some embodiments;

FIGS. 2E and 2F show multiple optical transmission systems according to some embodiments.

DETAILED DESCRIPTION

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Aspects of embodiments relate to systems, devices and methods that enable high data rate optical signals with reduced power consumption, reduced latency and reduced computational complexity. FIGS. 1A-1G show an optical system for data transmission according to some embodiments. As shown in FIG. 1A, an optical transmission system **100** includes transceivers **108-1** and **108-2**. Each transceiver **108** includes an optical transmitter **110**, an optical receiver **140**, and a controller **160**.

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Transmitter **110-1** is in optical communication with receiver **140-2** over a single mode fiber optic cable **170-1** for transmitting unidirectional data signals **102**, and transmitter **110-2** is in optical communication with receiver **140-1** over a single mode fiber optic cable **170-2** for transmitting unidirectional data signals **104**. In some embodiments, a single fiber optic cable **170** may be used for bidirectional optical communication such as by using different wavelengths for transmitting data signals **102** and **104**. Data signals, such as signals **102** and **104** are also referred to herein as “channels”. In some embodiments, each transceiver **108-1** and **108-2** is provided as an integrated circuit (IC) on a shared semiconductor substrate.

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Data signals **102**, **104** are electrical data signals. In some embodiments, data signals **102**, **104** are digital signals and the laser pulse repetition rate is equal or larger than the digital signal rate. In some embodiments, data signals **102**, **104** are analog electrical signals and the laser pulse repetition rate is equal or larger than the Nyquist frequency of the analog electrical signals. In some embodiments, data signals **102**, **104** are a combination of digital and analog

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signals. FIGS. 1A-1G illustrate transmission of two channels in each transmission direction (data signals **102-1** and **102-2** and data signals **104-1** and **104-2**) for simplicity but it should be appreciated that more than two channels may be multiplexed and transmitted by system **100**. In some embodiments, between 2-16 data signals per wavelength are supported.

5 A controller **160** is a computing device as defined herein. Controller **160-1** is in data communication with transmitter **110-1** and receiver **140-1**, and controller **160-2** is in data communication with transmitter **110-2** and receiver **140-2** for controlling each of transceivers **108-1** and **108-2** for the operation of system **100** as described further below.

The components of each transmitter **110** are further described with reference to FIG. 1B and include a pulsed laser **112**, a polarization splitter **114**, a 3dB splitter **116**, drivers **118**,
10 electro-optical (EO) modulators **120**, a tunable phase-shifter **122**, a 3dB coupler **124**, a polarization coupler **126** and a pulse shaper **128**. In some embodiments, the components of transmitter **110** are formed on a common semiconductor as an IC.

Pulsed laser **112** provides a source pulsed laser signal that may be modulated based on
15 data signals **102** for optical transmission of data signals **102**. The pulsed laser signal is also used as a clock and is transmitted along with the modulated data to enable demodulation of the data signal. In some embodiments, pulsed laser **112** operates at a fixed wavelength here denoted λ_1 . Pulsed laser **112** emits pulses at a periodic repetition rate. In some embodiments, pulsed laser **112** may be any one of a bulk laser, quantum well laser, quantum dot laser,
20 semiconductor mode-locked laser, high-power semiconductor laser or mode-locked integrated external-cavity surface emitting laser. In some embodiments, pulsed laser **112** may support a pulse repetition rate between 5 GHz to 100 GHz. In some embodiments, pulsed laser **112** may support a pulse repetition between 100 GHz - 400 GHz.

Polarization splitter **114** splits the pulsed laser signal into orthogonal transverse modes.
25 In system **100**, one mode is used for data transmission and the other mode is used for clock transmission. The data is transmitted on a data branch **113** in the TE (transverse electric) mode and the clock is transmitted on a clock branch **111** in the TM (transverse magnetic) mode, or vice versa (data on TM and clock on TE). In some embodiments, polarization splitter **114** splits the pulsed laser signal strength unequally between the two modes. Non-limiting
30 examples of split ratios include 90/10 and 80/20. In some embodiments, polarization splitter **114** splits the pulsed laser signal equally between the two modes. It is anticipated that both modes may suffer from the same distortions during transmission with no effect on the orthogonality.

In data branch **113**, transmitter **112** provides for OTDM of multiple data signals **102** (or **104**). Exemplarily, two data signals **102-1** and **102-2** as well as two drivers **118-1**, **118-2** and two EO modulators **120-1**, **120-2** are shown for simplicity, but it should be appreciated that multiple (more than two) data signals may be supported. 3dB splitter **116** splits the pulsed transverse mode laser signal according to the number of data signals supported (here shown as two). In some embodiments, each data signal **102** is input into transmitter **112** via drivers **118**. Driver **118** may supply power to EO modulator **120** and may adjust the electrical signal level of the input data signal **102**.

EO modulator **120** modulates the source pulsed laser signal based on input data signals **102**. In some embodiments, EO modulator may include a digital to analog converter (DAC) (not shown) for handling analog electrical inputs. In some embodiments, the pulse (clock) rate and thus the modulated channel rate is:

$$R / (\text{number of channels})$$

Various modulation schemes including but not limited to pulsed amplitude modulation (PAM) or quadrature amplitude modulation (QAM) can be applied. Tunable phase-shifter **122** shifts the phase of the second and further channels to obtain modulated (phase-shifted) channels (indicated as $\lambda_{1S1-MOD}$, $\lambda_{1S2-MOD, SHIFT}$) so that channel pulses will be interleaved when combined at 3dB coupler **124**. Coupler **124** combines the modulated (phase-shifted) channels (indicated as $\lambda_{1S1-MOD}$, $\lambda_{1S2-MOD, SHIFT}$) to form an OTDM output signal (indicated as λ_{1OTDM}) of data branch **113** having a pulse rate of:

$$R \times (\text{number of channels})$$

FIG. 1C shows illustrative signal amplitude graphs of the modulated (phase-shifted) channels (indicated as $\lambda_{1S1-MOD}$, $\lambda_{1S2-MOD, SHIFT}$) and the combined OTDM output (indicated as λ_{1OTDM}) of data branch **113** as well as the clock signal (indicated as λ_{1CLOCK}).

Polarization coupler **126** combines the transverse modes of the data and clock branches **111** and **113** to form orthogonal transverse signals carrying the OTDM output and the clock, indicated as $\lambda_{1OTDM + CLOCK}$. In some embodiments, pulse shaper **128** shapes and equalizes the pulse heights and shapes of $\lambda_{1OTDM + CLOCK}$ to form the transmitter output **106**. In some embodiments, pulse shaper **128** may be coupled to a fiber optic cable **170**. In some embodiments, pulse shaper **128** may feed into a WDM multiplexer as describe further below. In some embodiments, pulse shaping may be implemented using filter banks. In some embodiments, pulse shaping may be implemented using nested unbalanced Mach-Zehnder interferometers (MZIs), ring resonators, or a combination of MZIs and ring resonators. Transmitter output **106** is transmitted on fiber optic cable **170** towards receiver **140**.

In transmitter **110**, controller **160** may monitor and control all components and provide for automatic adjustment of adjustable components such as phase-shifters **122**, pulse shapers **128**, and drivers **118**.

The components of each receiver **140** are further described with reference to FIG. 1D and may include an optical amplifier (OA) **142**, a polarization splitter **144**, splitters **146**, polarization/phase controllers (PC) **148**, tunable phase-shifters **150**, dispersion managers **152**, saturable absorbers **154**, drivers **155**, circulators **156**, and output components **158**. In some embodiments, the components of receiver **140** may be formed on a common semiconductor substrate as an IC.

OA **142** boosts the signal received from transmitter **110**. In some embodiments, OA **142** may be coupled to fiber optic cable **170**. In some embodiments, OA **142** may be connected to a WDM demultiplexer as described further below. In some embodiments, OA **142** may be a quantum dot semiconductor optical amplifier that has low power consumption and minimal cross talk between different wavelengths. In some embodiments, a driver **145** may supply power to OA **142**.

The output of OA **142** ($\lambda_{1\text{ OTDM} + \text{CLOCK}}$) is fed into polarization splitter **144**, which splits the received signal ($\lambda_{1\text{ OTDM} + \text{CLOCK}}$) into orthogonal transverse modes. The data mode (TM or TE as defined in the transmitter) is transmitted on a data branch **141** and the clock mode (TM or TE as defined in the transmitter) is transmitted on a clock recovery branch **143**. In some embodiments, polarization splitter **144** splits the received signal unequally between the two modes. Non-limiting examples of split ratios include 90/10 and 80/20. In some embodiments, polarization splitter **144** splits the received signal equally between the two modes.

FIG. 1E shows illustrative signal amplitude graphs of the combined OTDM signal (here indicated as $\lambda_{1\text{ OTDM}}$) split within data branch **141**, the recovered clock and phase-shifted clocks (here indicated as $\lambda_{1\text{-CLOCK}}$, $\lambda_{1\text{-CLOCK SHIFT}}$) of clock branch **143** and the recovered modulated (phase-shifted) channels (here indicated as $\lambda_{1\text{ S1-MOD}}$, $\lambda_{1\text{ S2-MOD, SHIFT}}$).

In data branch **141**, splitter **146-1** splits the OTDM according to the number of channels that were time division multiplexed by transmitter **110**. Thus, each split of data branch **141** carries $\lambda_{1\text{ OTDM}}$. Similarly, in clock branch **143**, splitter **146-2** splits the clock signal $\lambda_{1\text{-CLOCK}}$ according to the number of channels that were time division multiplexed by transmitter **110**. As above, two OTDM channels and corresponding two clock channels are shown for simplicity, but it should be appreciated that multiple channels may be demultiplexed.

In some embodiments, polarization/phase controllers (PC) **148** may be provided for matching the polarization and to correct phase mismatches. Exemplarily, multiple PCs **148-**

1..148-4 are provided, each on a separate signal or clock branch. Tunable phase-shifters 150-1 and 150-2 shift the phase of the clock channels so that clock pulses will be timed to coincide with the interleaved channels of the OTDM signal in data branch 141. Each dispersion manager (DM) 152 may correct for dispersion in the optical channel that has affected the data and/or
 5 clock signals. Exemplarily, multiple DMs 152-1..152-4 are provided, each on a separate branch. DM 152 further may introduce pre-correction for dispersion introduced by a SA 154. In some embodiments, a DM 152 may include chirped Bragg gratings controlled by a temperature controller 153. In some embodiments, a driver 155 may supply power to a respective SA 154.

10 Each output of clock branch 143 (here indicated as λ_1 CLOCK and λ_1 CLOCK SHIFT) is fed into a corresponding circulator 156 in the data branch 141. Exemplarily, two circulators 156-1, 156-2, two SAs 154-1, 154-2, and two drivers 155-1, 155-2 are shown corresponding to two multiplexed data channels. In some embodiments, circulators 156 may be non-reciprocating, one directional, three-port circulators. In FIG. 1D, circulators 156 are shown as having a
 15 clockwise direction, but it should be appreciated that the direction employed will be functional. In use, the clock input is circulated to an SA 154. In some embodiments, each SA 154 may be any one of a quantum well (QW) semiconductor SA, a quantum dot SA, or a bulk semiconductor SA.

A clock pulse will saturate SA 154, forcing SA 154 to be transparent to thus “release” or
 20 “transmit” the current OTDM interleaved channel pulse through SA 154 corresponding to the pulse period. Thus, λ_1 CLOCK and λ_1 CLOCK SHIFT will each respectively saturate SA 154-1 and SA 154-2 at different time periods, each time period corresponding to a separate OTDM channel, to thereby release the current OTDM channel pulse through SA 154. When the clock signal is between pulses (low clock signal), SA 154 is not saturated, thus blocking other OTDM
 25 channels. In some embodiments, each SA 154-1 or 154-2 provides an electrical output of each recovered clock 159-1 or 159-2.

The released OTDM pulse will enter circulator 156 and will be circulated to output components (OC) 158. Each OC 158 includes those components necessary for converting the released optical channel back into an electrical data signal 102. Exemplarily, two OCs 158-1,
 30 158-2 are shown, corresponding to two multiplexed data channels. OC 158 may include one or more of a photodiode (PD) or a PD array for optical-to-electrical conversion, a transimpedance amplifier (TIA), a DAC, and/or a limiting amplifier (LA).

In receiver 140, controller 160 may monitor and control all components and provide for automatic adjustment of adjustable components such as phase-shifters 150, OA 142, drivers

145, **155**, and DMs **152**. In some embodiments, controller **160** monitors transceiver **108** performance in terms of one or more of bit error rate, data throughput, frame loss, jitter, and other parameters, and then performs adjustment of adjustable components (in both of transmitter **110** and receiver **140**) in order to optimize the transceiver **108** performance.

5 As shown in FIG. 1F, in some embodiments, multiple systems **100-1**, **100-2**, to **100-X** (where $X=N/2$) may be provided in parallel, each system **100** operating over a separate pair of fiber optic cables **170-1** and **170-2**. As further shown, each of systems **100** may provide OTDM of up to four channels in each direction (**102**, **104**). In some embodiments, more than four channels may be provided. Each of systems **100-1**, **100-2**, **100-X** may operate using a pulsed
10 laser **112** with the same wavelength or different wavelengths or a combination of wavelengths.

As shown in FIG. 1G, in some embodiments, multiple systems **100-1** to **100-X** may be provided in parallel along with a wavelength division multiplexing (WDM) multiplexers **172-1** and **174-2** and demultiplexers **172-2** and **174-1**, each operating over a respective single fiber optic cable **170-1** and **170-2**. For operation using WDM, each of systems **100-1**, **100-2**... **100-
15 N** uses a respective pulsed laser **112** with a different wavelength. As further shown in FIG. 1G, each of systems **100** may provide OTDM of up to four channels in each direction (**102**, **104**). In some embodiments, more than four channels may be provided.

FIGS. 2A-2F show an optical system for bidirectional data transmission over a full-
20 duplex fiber according to some embodiments. As shown in FIG. 2A, an optical transmission system **200** includes transceivers **208-1** and **208-2**. Each transceiver **208** includes an optical transmitter **210**, an optical receiver **240**, a coupling assembly **209**, and a controller **260**.

Transmitter **210-1** is in optical communication with receiver **240-2** over a full duplex fiber optic cable **270** for transmitting data signals **102** using a first wavelength (λ_1), and
25 transmitter **210-2** is in optical communication with receiver **240-1** over full duplex fiber optic cable **270** for transmitting data signals **104** using a second wavelength (λ_2). In some embodiments, each of transceivers **208** is provided as an IC on a shared semiconductor substrate.

Data signals **102**, **104** are electrical data signals. In some embodiments, data signals **102**,
30 **104** are digital signals and the laser pulse repetition rate is equal or larger than the digital signal rate. In some embodiments, data signals **102**, **104** are analog electrical signals and the laser pulse repetition rate is equal or larger to the Nyquist frequency of the analog electrical signals. In some embodiments, data signals **102**, **104** are a combination of digital and analog signals. FIGS. 2A-2F illustrate transmission of two channels in each transmission direction (data

signals **102-1** and **102-2** and data signals **104-1** and **104-2**) for simplicity but it should be appreciated that more than two channels may be transmitted by system **200**. In some embodiments, between 2-16 data signals per wavelength are supported.

Each controller **260** is a computing device as defined herein. Controller **260-1** is in data communication with transmitter **210-1** and receiver **240-1** and controller **260-2** is in data communication with transmitter **210-2** and receiver **240-2** for controlling each of transceivers **208-1** and **208-2** for the operation of system **200** as described further below. In some embodiments, each of coupling assembly **209-1**, **209-2** is in data communication with its respective controller **260-1**, **260-2**.

The components of each transmitter **210** are further described with reference to FIG. 2B and include a pulsed laser **112**, a splitter **214**, a 3dB splitter **116**, drivers **118**, EO modulators **120**, a tunable phase-shifter **122**, a 3dB coupler **124**, and pulse shapers **228**. In some embodiments, the components of transmitter **210** are formed on a common semiconductor as an IC. Like numbered components of transmitter **110** are the same components and provide the same functionality in transmitter **210** and are therefore not described again.

Splitter **214** splits the pulsed laser signal into a data branch **213** for preparing an OTDM signal for transmission and into a clock branch **211** for clock transmission. In some embodiments, splitter **214** splits the pulsed laser signal strength unequally between the two branches. Non-limiting examples of split ratios include 90/10 and 80/20. In some embodiments, splitter **214** splits the pulsed laser signal equally between the two branches.

In data branch **213**, transmitter **212** provides for OTDM of multiple data signals **102** (or **104**). Two data signals **102-1** and **102-2** are shown for simplicity but it should be appreciated that multiple data signals may be supported. Data branch **213** functionality is the same as for system **100** and forms the OTDM output (indicated as $\lambda_{1 \text{ OTDM}}$) of data branch **213** having a pulse rate of $R \times (\text{number of channels})$.

In some embodiments, pulse shaper **228-1** shapes and equalizes the pulse heights and shapes of $\lambda_{1 \text{ OTDM}}$. In some embodiments, pulse shaper **228-2** shapes and equalizes the pulse heights of $\lambda_{1 \text{ CLOCK}}$. In some embodiments, pulse shaping may be implemented using filter banks. In some embodiments, pulse shaping may be implemented using nested unbalanced MZIs or ring resonators or a combination of MZIs and ring resonators.

As shown in FIG. 2C, the output of transmitter **210** feeds into coupling assembly **209**. Each coupling assembly **209** includes circulators **230** and couplers **232**. Pulse shaper **228-1** feeds $\lambda_{1 \text{ OTDM}}$ into optical circulator **230-1** and pulse shaper **228-2** feeds $\lambda_{1 \text{ CLOCK}}$ into optical circulator **230-2**. In some embodiments, circulators **230** may be a non-reciprocating, one

directional, three-port circulators. In FIG. 2C circulators **230** are shown as having a clockwise direction, but It should be appreciated that the direction employed will be functional.

One of the circulator **230** ports is connected to couplers **232**. Coupler **232-1** couples the outgoing (Tx) λ_1 OTDM to a first of the fibers in cable **270** and coupler **232-2** couples outgoing
 5 λ_1 CLOCK to a second of the fibers in fiber optic cable **270**. The incoming (Rx) clock and OTDM signals λ_2 OTDM and λ_2 CLOCK from cable **270**, exit couplers **232** and are directed by circulators **230** to exit ports of circulators **230** that are coupled to a “same-side” receiver **240** input.

In transmitter **210**, controller **160** may monitor and control all components and provide for automatic adjustment of adjustable components such as phase-shifters **122**, pulse shapers
 10 **228**, and drivers **118**.

The components of each receiver **140** are further described with reference to FIG. 2D and may include optical amplifiers (OA) **242**, splitters **146**, polarization/phase controllers (PC) **148**, tunable phase-shifters **150**, dispersion managers **152**, saturable absorbers **154**, drivers **155**, circulators **156**, and output components **158**. In some embodiments, the components of
 15 receiver **240** may be formed on a common semiconductor as an IC. Like numbered components of receiver **140** are the same components and provide the same functionality in receiver **240** and are therefore not described again.

OA **242-1** boosts the OTDM signal received from transmitter **210**. OA **242-2** boosts the clock signal received from transmitter **210**. Both of OAs **242** may be coupled to fiber optic
 20 cable **270** via coupling assembly **209**. In some embodiments, OA **242** may be connected to a WDM demultiplexer as described further below. In some embodiments, OA **242** may be a quantum dot semiconductor optical amplifier that has low power consumption and minimal cross talk between different wavelengths. In some embodiments, drivers **245** may supply power to OAs **242**.

The output of OA **242-1** is fed into a data branch **241** and the output of OA **242-2** is transmitted on a clock branch **243**. The functionality and operation of data branch **241** are the same as data branch **141** as described above, and the functionality and operation of clock branch
 25 **243** are the same as clock branch **143** as described above.

In receiver **240**, controller **260** may monitor and control all components and provide for automatic adjustment of adjustable components such as phase-shifters **150**, OAs **242**, drivers
 30 **155**, and DMs **152**. In some embodiments, controller **260** monitors transceiver **208** performance in terms of one or more of bit error rate, data throughput, frame loss, jitter, and other parameters, and then performs adjustment of adjustable components (in both of transmitter **210** and receiver **240**) in order to optimize the transceiver **208** performance.

As shown in FIG. 2E, in some embodiments, multiple systems **200-1**, **200-2**, to **200-X** (where $X=N/2$) may be provided in parallel each operating over a separate full duplex fiber optic cable **270-1**, **270-2** ... **270-X**. As further shown, each of systems **200** may provide OTDM of up to four channels in each direction (**102**, **104**). In some embodiments, more than four
5 channels may be provided. Each of systems **200-1**, **200-2**... **200-X** may operate using a pulsed laser **112** with the same wavelength or different wavelengths or a combination of wavelengths.

As shown in FIG. 2F, in some embodiments, multiple systems **200** may be provided in parallel along with a dual WDM multiplexers **272-1** and **272-2** and demultiplexers **274-1** and **274-2** operating over a full duplex fiber optic cable **270**. For simplicity only one direction of
10 transmission is shown in FIG 2F. OTDM signals are transmitted using WDM pair **272-1** and **274-1** and clock signals are transmitted using WDM pair **272-2** and **274-2**. In some embodiments, one OA **242** is positioned before demultiplexer **274-1** and one OA **242** is positioned before demultiplexer **274-2**. For operation using WDM, each of systems **200-1**, **200-2**... **200-X** uses a pulsed laser **112** with a different wavelength. As further shown, each
15 of systems **200** may provide OTDM of up to four channels. In some embodiments, more than four channels may be provided.

In the claims or specification of the present application, unless otherwise stated, adjectives such as “substantially” and “about” modifying a condition or relationship characteristic of a feature or features of an embodiment of the invention, are understood to
20 mean that the condition or characteristic is defined to within tolerances that are acceptable for operation of the embodiment for an application for which it is intended.

Implementation of the method and system of the present disclosure may involve performing or completing certain selected tasks or steps manually, automatically, or a combination thereof. Moreover, according to actual instrumentation and equipment of
25 preferred embodiments of the method and system of the present disclosure, several selected steps may be implemented by hardware (HW) or by software (SW) on any operating system of any firmware, or by a combination thereof. For example, as hardware, selected steps of the disclosure could be implemented as a chip or a circuit. As software or algorithm, selected steps of the disclosure could be implemented as a plurality of software instructions being executed
30 by a computer using any suitable operating system. In any case, selected steps of the method and system of the disclosure could be described as being performed by a data processor, such as a computing platform for executing a plurality of instructions.

Although the present disclosure is described with regard to a computing device, or a computer, it should be noted that optionally any device featuring a data processor and the ability

to execute one or more instructions may be described as a computing device, including but not limited to any type of personal computer (PC), a server, a distributed server, a master control unit, a virtual server, a cloud computing platform, a cellular telephone, an IP telephone, a smartphone, a smart watch or a PDA (personal digital assistant). Any two or more of such
5 devices in communication with each other may optionally form a "network" or a "computer network".

It should be understood that where the claims or specification refer to "a" or "an" element, such reference is not to be construed as there being only one of that element. In the description and claims of the present application, each of the verbs, "comprise" "include" and "have", and
10 conjugates thereof, are used to indicate that the object or objects of the verb are not necessarily a complete listing of components, elements or parts of the subject or subjects of the verb.

While this disclosure describes a limited number of embodiments, it will be appreciated that many variations, modifications and other applications of such embodiments may be made. The disclosure is to be understood as not limited by the specific embodiments described herein,
15 but only by the scope of the appended claims.

WHAT IS CLAIMED IS:

1. A system, comprising:
 - an optical transmitter that includes a pulsed laser for outputting a pulsed laser signal, wherein the optical transmitter is configured to modulate the pulsed laser signal based on a plurality of data signals to form a plurality of modulated optical data signals, to optically time division multiplex the plurality of modulated optical data signals to obtain a multiplexed optical data signal, and to transmit the multiplexed optical data signal together with an optical clock signal derived from the pulsed laser signal; and
 - an optical receiver that includes a clock recovery branch and a data branch, wherein the clock recovery branch is configured to recover and phase-shift the optical clock signal into a plurality of phase-shifted recovered optical clock signals, wherein the data branch includes a plurality of saturable absorbers (SA), and wherein each SA is in optical communication with one of the plurality of phase-shifted recovered optical clock signals and is configured to receive the multiplexed optical data signal and to transmit one of the modulated optical data signals received in the multiplexed optical data signal according to the one of the plurality of phase-shifted recovered optical clock signals.
2. The system of claim 1, wherein the optical clock signal and the multiplexed optical data signal are transmitted by the optical transmitter in orthogonal transverse modes over a single mode fiber optic cable.
3. The system of claim 1, wherein the optical clock signal and the multiplexed optical data signal are each transmitted by the optical transmitter over a separate cable in a full-duplex fiber optic cable.
4. The system of claim 1, wherein a clock pulse from one of the plurality of phase-shifted recovered optical clock signals saturates a respective SA to thereby cause the respective SA to release a pulse from one of the plurality of modulated optical data signals.
5. The system of claim 1, wherein the clock recovery branch includes a splitter and a phase-shifter for extracting the optical clock signal into the plurality of phase-shifted extracted optical clock signals phase-shifted recovered optical clock signals.

6. The system of claim 1, wherein the optical receiver further includes one or more dispersion managers configured for dispersion correction of the plurality of modulated optical data signals and the plurality of phase-shifted recovered optical clock signals.
7. The system of claim 1, wherein the optical receiver further comprises output components configured for extracting the plurality of data signals from each of the plurality of modulated optical data signals.
8. The system of claim 1, wherein the pulsed laser is selected from the group consisting of a bulk laser, a quantum well laser, a quantum dot laser, a semiconductor mode-locked laser and a mode-locked integrated external-cavity surface emitting laser.
9. The system of claim 1, wherein the pulsed laser has a pulse repetition rate between 5 GHz to 100 GHz.
10. The system of claim 1, wherein the optical receiver includes an optical amplifier (OA).
11. The system of claim 10, wherein the OA is a quantum dot semiconductor optical amplifier.
12. The system of claim 1, wherein the modulation is one of a pulsed amplitude modulation (PAM) or a quadrature amplitude modulation (QAM).
13. The system of claim 1, wherein the plurality of data signals includes between 2-16 data signals per wavelength.
14. The system of claim 1, wherein the plurality of data signals includes digital signals and/or analog signals.
15. A transmission system, comprising:
 - a first transceiver; and
 - a second transceiver,wherein each of the first and second transceivers includes an optical transmitter, an optical receiver and a controller,

wherein each optical transmitter is configured to modulate the pulsed laser signal based on a plurality of data signals to form a plurality of modulated optical data signals, to optically time division multiplex the plurality of modulated optical data signals to obtain a multiplexed optical data signal, and to transmit the multiplexed optical data signal together with an optical clock signal derived from the pulsed laser signal,

and wherein each optical receiver includes a clock recovery branch and a data branch, wherein the clock recovery branch is configured to recover and phase-shift the optical clock signal into a plurality of phase-shifted recovered optical clock signals,

wherein the data branch includes a plurality of saturable absorbers (SA), and

wherein each SA is in optical communication with one of the plurality of phase-shifted recovered optical clock signals and is configured to receive the multiplexed optical data signal and to transmit one of the modulated optical data signals received in the multiplexed optical data signal according to the one of the plurality of phase-shifted recovered optical clock signals.

16. The transmission system of claim 15, wherein each controller is configured for monitoring transceiver performance and for performing adjustment of the transmitter and receiver in order to optimize the transceiver performance.

17. The transmission system of claim 16, wherein the monitoring includes monitoring of one or more of bit error rate, data throughput, frame loss, or jitter.

18. The transmission system of claim 15, wherein each transceiver is formed on a common semiconductor substrate as an IC.