Optical Modulator with Linear Response

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(54) **OPTICAL MODULATOR WITH LINEAR RESPONSE**

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PCT Pub. Date: **Mar. 17, 2011**

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(51) **Int. Cl.**

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H04B 10/50	(2013.01)
H04B 10/548	(2013.01)
H01S 5/065	(2006.01)
H01S 5/40	(2006.01)
H01S 5/00	(2006.01)

(52) **U.S. Cl.**
CPC ***H01S 5/0656*** (2013.01); ***H04B 10/505*** (2013.01); *H01S 5/4012* (2013.01); *H01S 5/0085* (2013.01); ***H04B 10/548*** (2013.01)
USPC **398/188**; 398/195; 398/198

(58) **Field of Classification Search**
USPC 398/188
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,769,853	A *	9/1988	Goodwin et al.	398/188
6,963,442	B2 *	11/2005	Yap et al.	359/326
2002/0159668	A1 *	10/2002	Williams et al.	385/3
2003/0231601	A1 *	12/2003	Kim	370/277

OTHER PUBLICATIONS

Nemitz, Setup of a stable high-resolution laser system, 2004, University of Stuttgart, pp. 38-40.*

(Continued)

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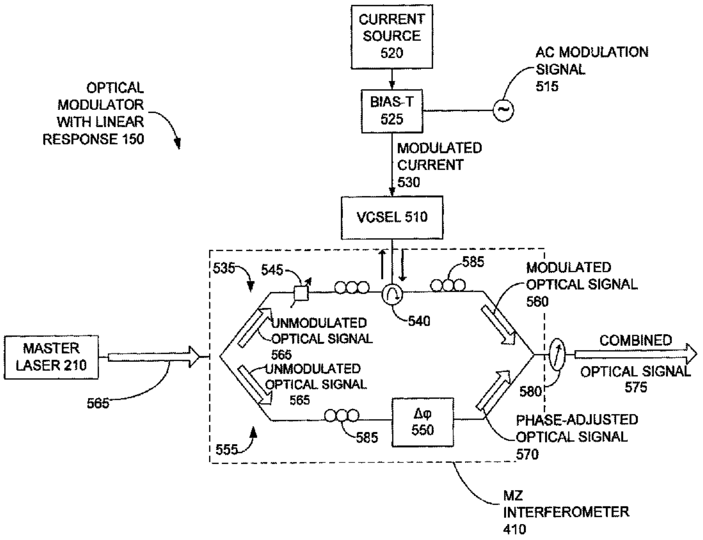
(57) **ABSTRACT**

Apparatuses and methods for modulating an optical signal are disclosed. One embodiment is a method comprising: phase modulating a slave laser which is injection locked to a master laser to produce an arcsine phase modulated optical signal, and combining the arcsine phase modulated optical signal with an output optical signal from the master laser.

4 Claims, 5 Drawing Sheets



(56) References Cited

OTHER PUBLICATIONS

Ramos et al., Optical Injection Locking and Phase-lock loop Combined Systems, 1994, Optical Society of America, Optics Letters, vol. 19, No. 1, pp. 4-6.*

Chrostowski, Optical Injection Locking of Vertical Cavity Surface Emitting Lasers, 2003, University of California at Berkeley, pp. 3-7.*

Grattan et al., Optical Fiber Sensor Technology, 2000, Kluwer Academic Publisher, pp. 118-119.*

Collett, Polarized Light in Fiber Optics, 2003, the PolaWave Group, p. 257.*

* cited by examiner

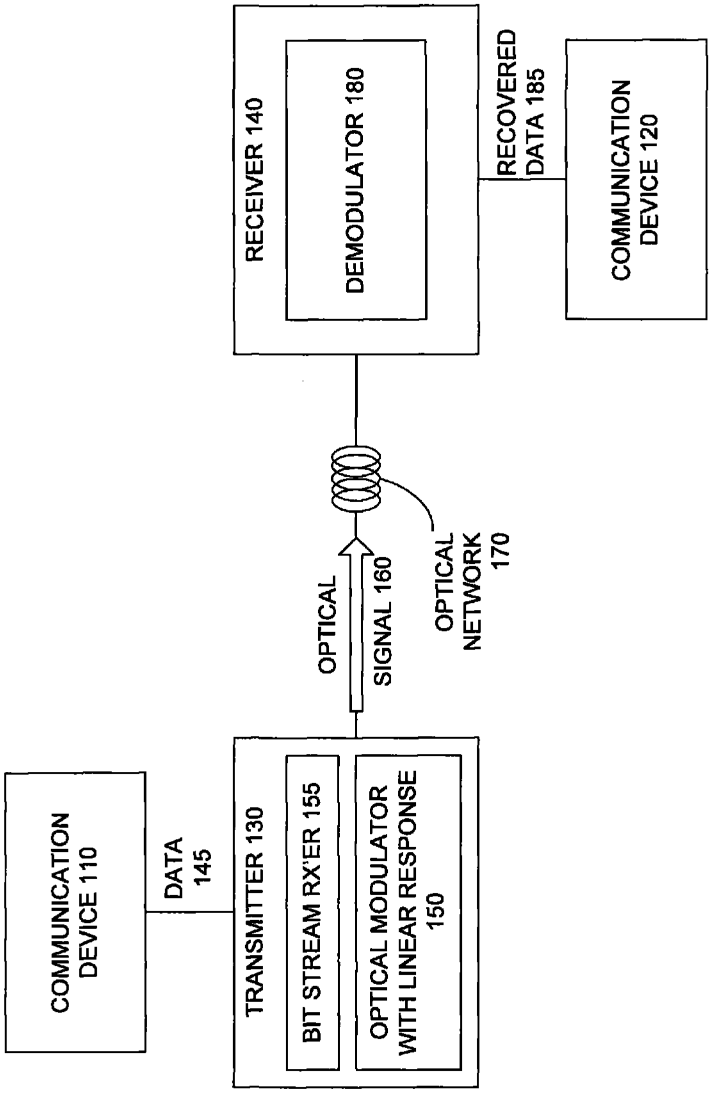

COMMUNICATION DEVICE 110
DATA 145
TRANSMITTER 130
BIT STREAM RX'ER 155
OPTICAL MODULATOR WITH LINEAR RESPONSE 150
OPTICAL SIGNAL 160
OPTICAL NETWORK 170
RECEIVER 140
DEMODULATOR 180
RECOVERED DATA 185
COMMUNICATION DEVICE 120

FIG. 1

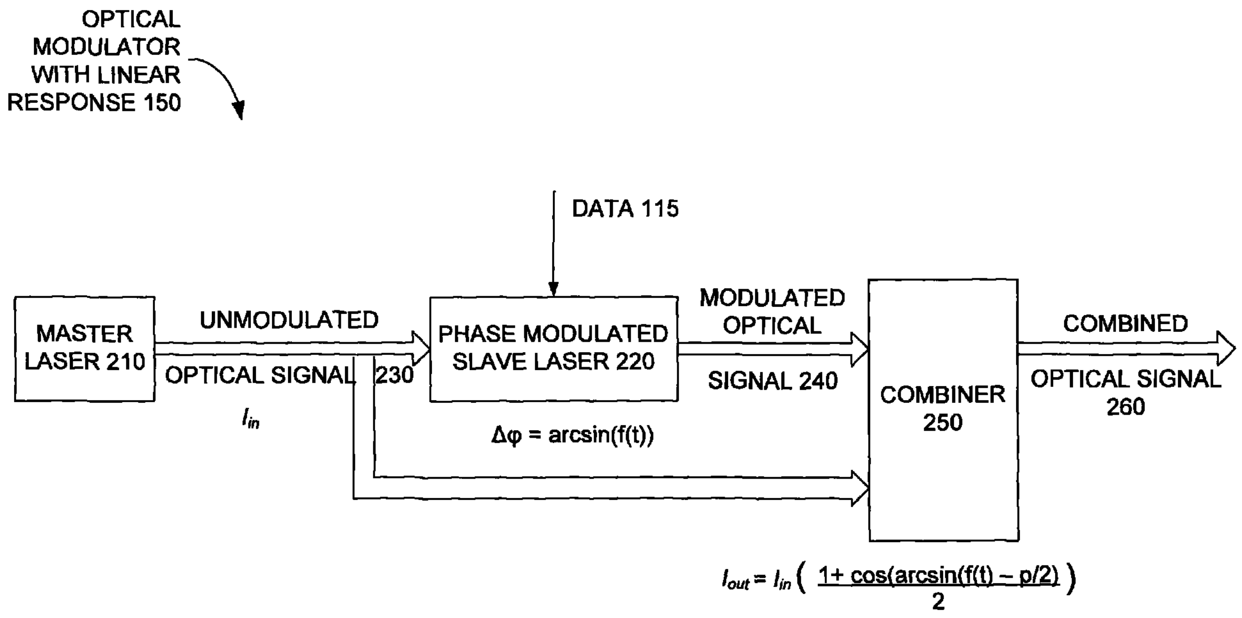

OPTICAL MODULATOR WITH LINEAR RESPONSE 150
DATA 115
MASTER LASER 210
UNMODULATED OPTICAL SIGNAL 230
I_{in}
PHASE MODULATED SLAVE LASER 220
$\Delta\varphi$ = arcsin(f(t))
MODULATED OPTICAL SIGNAL 240
COMBINER 250
COMBINED OPTICAL SIGNAL 260
$I_{out} = I_{in} \left(\frac{1 + \cos(\arcsin(f(t) - p/2)}{2} \right)$

FIG. 2

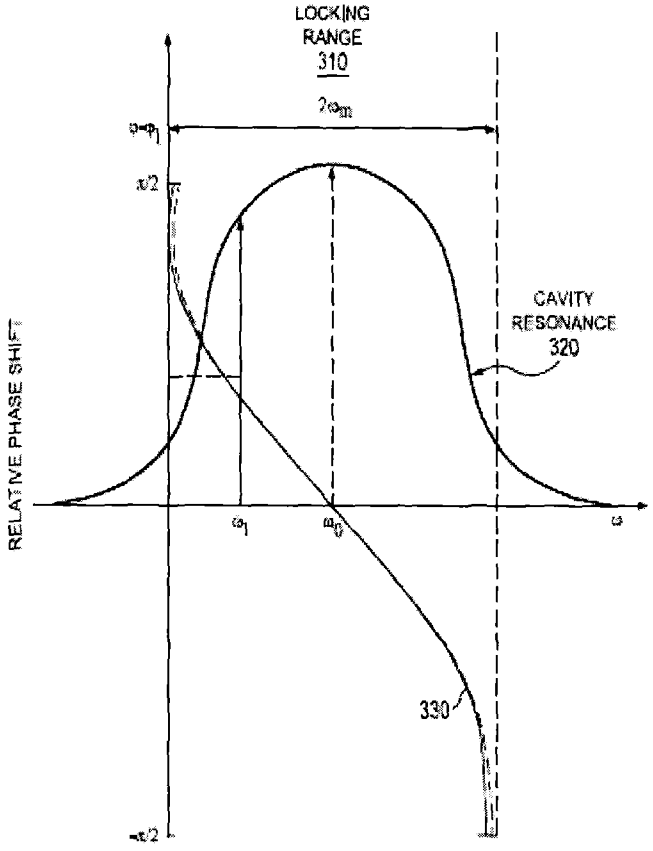

LOCKING RANGE
310
2ωm
φ=φ1
π/2
CAVITY RESONANCE
320
RELATIVE PHASE SHIFT
ω1
ω0
ω
330
-π/2

FIG. 3

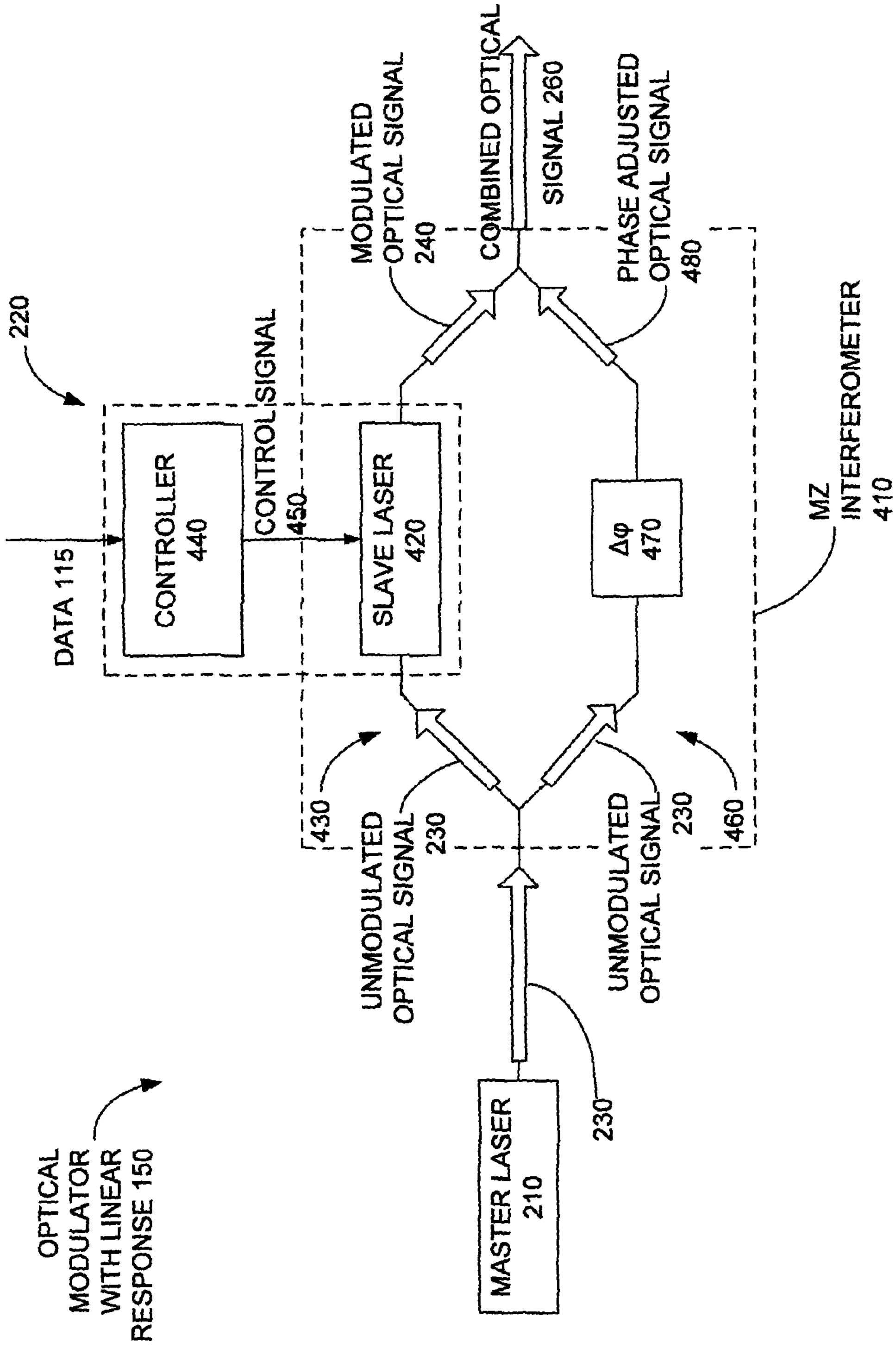

OPTICAL MODULATOR WITH LINEAR RESPONSE 150
DATA 115
220
CONTROLLER 440
CONTROL SIGNAL 450
SLAVE LASER 420
MASTER LASER 210
230
UNMODULATED OPTICAL SIGNAL 230
UNMODULATED OPTICAL SIGNAL 230
430
460
Δφ 470
MODULATED OPTICAL SIGNAL 240
COMBINED OPTICAL SIGNAL 260
PHASE ADJUSTED OPTICAL SIGNAL 480
MZ INTERFEROMETER 410

FIG. 4

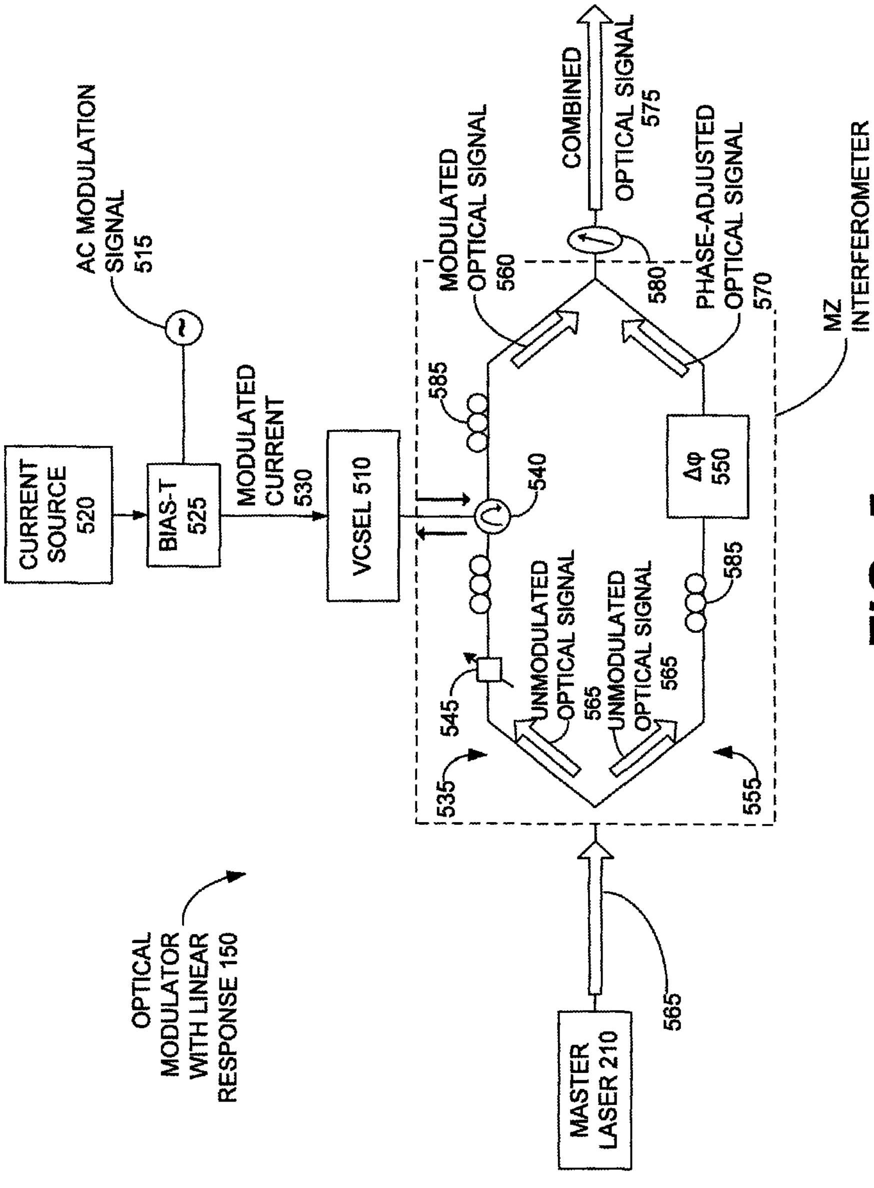

OPTICAL MODULATOR WITH LINEAR RESPONSE 150
CURRENT SOURCE 520
BIAS-T 525
AC MODULATION SIGNAL 515
MODULATED CURRENT 530
VCSEL 510
540
585
545
535
555
UNMODULATED OPTICAL SIGNAL 565
UNMODULATED OPTICAL SIGNAL 565
Δφ 550
585
MODULATED OPTICAL SIGNAL 560
PHASE-ADJUSTED OPTICAL SIGNAL 570
580
COMBINED OPTICAL SIGNAL 575
MZ INTERFEROMETER 410
MASTER LASER 210
565

FIG. 5

OPTICAL MODULATOR WITH LINEAR RESPONSE

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a National Stage entry under 35 U.S.C. 371 of PCT/US2010/023306 filed on Feb. 5, 2010, which claims priority to U.S. Provisional Patent Application Ser. No: 61/240,724, filed Sep. 9, 2009, the entireties of which are hereby incorporated by reference.

FIELD OF THE DISCLOSURE

The present disclosure relates to optical communication.

BACKGROUND

Optical modulators have a variety of applications, for example, in signal processing, optical communication, and radio frequency (RF) communication. Conventional electro-optic modulators have an optical modulation transfer function that is inherently nonlinear, which limits the spurious free dynamic range (SFDR) of such modulators. Another conventional approach uses direct modulation of the optical intensity of a laser, but chirp and inefficient power handling are typically drawbacks to this approach.

BRIEF DESCRIPTION OF THE DRAWINGS

Many aspects of the disclosure can be better understood with reference to the following drawings. The components in the drawings are not necessarily to scale, emphasis instead being placed upon clearly illustrating the principles of the present disclosure.

FIG. **1** is a block diagram of an environment in which one embodiment of an optical modulator with linear response is located.

FIG. **2** is a block diagram of the optical modulator from FIG. **1**, according to some embodiments.

FIG. **3** is a graph illustrating the phase response of the modulated optical signal produced by the optical modulator from FIG. **1**, according to some embodiments.

FIG. **4** is a diagram of the structure of the optical modulator from FIG. **1**, according to some embodiments.

FIG. **5** is a block diagram showing additional detail of one embodiment of the optical modulator from FIG. **1**, according to some embodiments.

DETAILED DESCRIPTION

An optical modulator with linear response is disclosed herein. This modulator offers improved spurious free dynamic range as compared to conventional approaches. The linear response is achieved by phase modulating the output of an injection locked slave laser, or modulating the resonance of an injection locked slave laser, and combining the modulated output with the injection source signal from the master laser. In some embodiments, the phase is modulated in an arcsine fashion by tuning the cavity resonance of the slave laser. In some embodiments, the slave laser resides in one arm of a Mach-Zehnder interferometer. In some embodiments, the injection locked slave laser is a vertical cavity surface emitting laser (VCSEL), and a static phase shift is introduced at the output of the VCSEL by detuning the resonant frequency from the injection frequency.

FIG. **1** is a block diagram of an environment in which one embodiment of an optical modulator with linear response is located. Communication devices **110** and **120** communicate through a transmitter **130** and a receiver **140**. The communication devices **110**, **120** may be computing devices which act as communication endpoints, or may be communication intermediaries such as routers, switches, multiplexers, and/or other components. The communication device **110** provides data **145** to the transmitter **130**. An optical modulator with linear response **150**, which may be considered part of the transmitter **130**, performs phase modulation on an optical beam, thus encoding the data **145**. In some embodiments, the transmitter **130** also includes a bit stream receiver **155** that receives the data **145**, and which may perform compression, channel encoding, and/or encryption on the data **145** before providing the data **145** to the modulator **150**.

The resulting optical signal **160** is transmitted over an optical network **170** to the receiver **140**. A demodulator **180** performs demodulation on the received optical signal **160**, then supplies the resulting recovered data **185** to the other communication device **120**. The recovered data **185** contains the same information as the original data **145**.

Although the modulator **150**, the demodulator **180**, and the optical network **170** process signals in the optical domain, some embodiments of the transmitter **130** and the receiver **140** operate at least partially in the electrical domain, such that the data **145** and the recovered data **185** are represented by electrical and/or electronic signals rather than optical signals. Although the optical modulator with linear response **150** is shown in FIG. **1** as part of the transmitter **130**, this is merely a logical representation. While some embodiments may use a modulator **150** which resides in the transmitter device, in other embodiments the modulator **150** may be physically separate from, but in communication with, other components of the transmitter **130**. Finally, the optical network **170** may include a variety of components such as amplifiers, repeaters, multiplexers, switches, cross-connects, and/or other components. Since these components are not necessary to explain the operation of optical modulator with linear response **150**, they are not shown in FIG. **1** and will not be discussed further.

FIG. **2** is a block diagram of the optical modulator with linear response **150**, according to some embodiments. The optical modulator with linear response **150** includes a master laser **210** and a phase modulated slave laser **220**. The slave laser **220** is injection-locked to the master laser **210**. Thus, the output frequency of the slave laser **220** is locked to the output frequency of the master laser **210** as long as the difference between the master frequency and the free-running frequency of the slave stays within a particular range associated with the slave laser **220**, known as the locking range. Any type of laser that is capable of injection locking can be used as the slave laser **220**. In some embodiments, the slave laser **220** is a vertical cavity surface emitting laser (VCSEL). Other variations include, but are not limited to, a Fabry-Pérot laser, a distributed feedback laser (DFB), a ring laser, and an erbium laser.

The unmodulated optical signal **230** is injected into the slave laser **220**. The slave laser **220** phase modulates its laser output in accordance with the data **145** to produce a modulated optical signal **240**. The phase of the modulated optical signal **240** varies in an arcsine manner. This behavior can be seen in FIG. **3**, which is a graph illustrating the phase response of the modulated optical signal **240** within the locking range **310** of the slave laser **220**. As can be seen in the graph, the phase shift **330** of the modulated optical signal **240** (relative to the phase of the master laser output) varies with the resonance frequency **320** of the slave cavity, in an arcsine manner.

Specifically, the phase of the modulated optical signal **240** is related to the difference between the injected signal frequency and the slave cavity resonance frequency **320**. This relationship is given by Equation 1:

$$\varphi(\omega_1) = \arcsin\left(\frac{(\omega_0 - \omega_1)}{\omega_m}\right),$$

where ω_1 is the injected signal frequency, ω_0 is the slave cavity resonance frequency, and ω_m is half of the locking range **310** of the slave laser **220**. Thus, tuning the cavity resonance of the slave laser **220** results in modulating the phase of the slave laser's output in an arcsine manner.

Returning to FIG. **2**, the arcsine phase modulated optical signal **240** from the slave laser **220** is combined (**250**) with the unmodulated optical signal **230** from the master laser **210**, to produce a combined optical signal **260**. In some embodiments, the combiner **250** takes the form of a Mach-Zehnder (MZ) interferometer. The combination of optical signals can be described by Equation 2:

$$I_{out} = I_{in}\left(\frac{1 + \cos(\arcsin(f(t) - \pi/2))}{2}\right),$$

which can be reduced to Equation 3:

$$I_{out} = I_{in}\left(\frac{1 + f(t)}{2}\right).$$

As can be seen from Equation 3, the combined optical signal **260** is directly proportional to the input signal **230** that is provided by the master laser **210**. Thus, the optical modulator with linear response **150** has a linear optical modulation transfer function. This linearity leads to increased spurious free dynamic range (SFDR) as compared to conventional electro-optic modulators, which have an inherent nonlinear optical modulation transfer function. Phase modulating by modulating a detuning between the cavity resonance of the slave laser and the master laser thus produces improved transmission characteristics.

FIG. **4** is a diagram of the structure of the optical modulator with linear response **150**, according to some embodiments. In the embodiment of FIG. **4**, the optical modulator with linear response **150** includes a Mach-Zehnder (MZ) interferometer **410**. The output **230** of the master laser **210** is coupled to the input of the MZ interferometer **410**. The resonant cavity of a slave laser **420** is located in a first arm **430** of the MZ interferometer **410**, so that the unmodulated optical signal **230** is input to the slave laser **420**. The slave laser **420** is injection-locked to the master laser **210**, with the slave resonant cavity being used either in reflection or transmission mode depending on the type of resonant cavity used. A control circuit or controller **440** provides a control signal **450** to the slave laser **420**, resulting in a modulated optical signal **240** output from the slave laser **420**.

The MZ interferometer **410** combines the phase modulated optical signal **240** from the arm containing the slave laser **420** with the unmodulated optical signal **230** passing through from a second arm **460** of the interferometer **410**. As described above in connection with FIGS. **2** and **3**, the injection locked slave laser **420** produces an arcsine phase shift in the input signal **230** according to the control signal **450**. This arcsine phase shift is given by $\Delta\phi = \arcsin(f(t))$ (Equation 4), where f(t) corresponds to, or is included in, the control signal **450**.

The combination of this phase modulated optical signal **240** with the unmodulated optical signal **230** is a combined optical signal **260**. As described above in connection with FIGS. **2** and **3**, the combined optical signal **260** has a linear relationship to the input signal **230**, given by

$$I_{out} = I_{in}\left(\frac{1 + f(t)}{2}\right)$$

(Equation 3 from above).

An optical phase shifter **470** is located in the second arm **460** of the interferometer **410**, in order to adjust the differential phase of the interferometer **410** to π/2. As also described above in connection with FIGS. **2** and **3**, the combination of this phase modulated optical signal **240** with the phase adjusted unmodulated signal **480** is a combined optical signal **260** which has a linear relationship to the input signal **230**, given by

$$I_{out} = I_{in}\left(\frac{1 + f(t)}{2}\right).$$

FIG. **5** is a block diagram showing additional detail of an embodiment of the optical modulator with linear response **150**. The output of a master laser **210** is provided to an MZ interferometer **410**. A vertical cavity surface emitting laser (VCSEL) **510** is injection locked to the master laser **210**, and thus operates as a slave to the master. Phase modulation of the slave is achieved by modulating the driving current of the VCSEL **510**. In this regard, an AC modulation signal **515** is combined with a fixed current source **520** using a bias-T junction **525**. The bias-T junction **525** places the AC modulation signal **515** on top of the fixed DC driving current of the VCSEL **510**, which modulates the driving current (within the locking range) around a fixed bias point. The resulting modulated current **530** is supplied to the VCSEL **510**, the effect of which is to tune the cavity resonance of the VCSEL **510**.

The VCSEL **510** is coupled to a first arm **535** of the interferometer **410** through an optical circulator **540**, such that the VCSEL **510** receives input from the master laser **210** and the VCSEL output exits the interferometer **410**. A variable optical attenuator **545** controls the amount of optical power from the master laser **210** that is injected into the VCSEL **510**. The ratio of injected power to output power by the VCSEL **510** affects the locking range of the VCSEL **510**. An optical phase shifter **550** is located in a second arm **555** of the interferometer **410** in order to adjust the differential phase of the interferometer **410** to π/2.

The interferometer **410** combines the phase modulated optical output **560** of the VCSEL **510** with the unmodulated optical signal **565** from the master laser **210**. As noted earlier, modulating the current of the injection-locked VCSEL **510** results in an arcsine modulation of the input signal **565** according to the AC modulated current signal **530**. This arcsine shift is given by $\Delta\phi = \arcsin(f(t))$ (Equation 4), where f(t) corresponds to the AC modulation signal **515**.

Combining this arcsine modulated signal **560** with the phase-adjusted signal **570** (i.e., the unmodulated signal in quadrature) produces a combined optical signal **575** which has a linear optical modulation transfer function. The example embodiment of FIG. **5** also includes a polarizer **580** at the output of the MZ interferometer **410** to match the polarization of interfering signals, and polarization controllers **585** are used in both arms **535**, **555** of the interferometer **410**. A person of ordinary skill in the art should appreciate that if the polarizations are not matched, the depth of modulation of the modulator output signal will decrease.

The foregoing disclosure as been presented for purposes of illustration and description. The disclosure is not intended to be exhaustive or to limit the disclosure to the precise forms disclosed. Various modifications or variations are possible in light of the above teachings. The implementations discussed, however, were chosen and described to illustrate the principles of the disclosure and their practical application to thereby enable one of ordinary skill in the art to utilize the disclosure in various implementations and with various modifications as are suited to the particular use contemplated. All such modifications and variations are within the scope of the disclosure as determined by the appended claims when interpreted in accordance with the breadth to which they are fairly and legally entitled.

What is claimed is:

1. An optical transmitter comprising:

a bit stream receiver configured to receive data; and

an optical modulator, the optical modulator comprising:

a Mach-Zehnder (MZ) interferometer having a pair of arms; a master laser operatively coupled to an input of the MZ interferometer and producing an injected signal;

a slave laser having an optical resonant cavity located in one of the pair of arms, the slave laser being injection-locked to the master laser, the slave laser configured to perform phase modulation on an optical signal thereby encoding the data as a phase modulated optical signal, the phase modulated optical signal having an arcsine phase shift relative to the injected signal; and

an optical phase shifter located in the other of the pair of arms.

2. The optical transmitter of claim **1**, wherein the slave laser is a vertical cavity surface emitting laser (VCSEL).

3. The optical transmitter of claim **1**, wherein the slave laser is a vertical cavity surface emitting laser (VCSEL) having a drive current input.

4. The optical transmitter of claim **1**, wherein the slave laser is a vertical cavity surface emitting laser (VCSEL) having a drive current input, the optical transmitter further comprising:

a current source; and

a bias-T junction operative to combine the current source and a modulated data signal, to produce the drive current input to the VCSEL.

* * * * *