

RESONATOR-ASSISTED CONTROL OF RADIO-FREQUENCY RESPONSE IN AN OPTICAL MODULATOR

CROSS-REFERENCE TO RELATED APPLICATIONS

5 This application is a continuation-in-part (CIP) of U.S. patent application Ser. No. 11/869,205, filed Oct. 9, 2007, and entitled "Resonator-Assisted Control of Radio-Frequency Response in an Optical Modulator," which is incorporated herein by reference in its entirety.

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10 Projects Agency (EPIC-DARPA). The Government has certain rights in this invention.

BACKGROUND OF THE INVENTION

1. Field of the Invention

 The present invention relates to optical communication equipment and, more
15 specifically, to optical modulators.

2. Description of the Related Art

 An optical modulator is one of the key enabling components of an optical communication system. With the rapidly growing demand for reliable and inexpensive optical
20 modulators, practical viable solutions to improving modulator characteristics are very desirable. One of such characteristics is the modulator's radio-frequency response. Typically, the modulator's ability to impart modulation on an optical beam weakens as the modulation frequency increases. In the optical domain, the frequency-response roll-off affects the modulator bandwidth and can, e.g., distort modulation sidebands, thereby adversely affecting
25 the optical-signal quality.

SUMMARY OF THE INVENTION

 According to one embodiment, an optical modulator has a Mach-Zehnder interferometer (MZI) and an optical resonator coupled, via a tunable optical coupler, to one of the MZI internal
30 arms. The optical resonator induces in the MZI frequency-dependent optical losses that can be represented by a comb of spectral resonances. The coupling strength between the optical

resonator and the MZI set by the optical coupler controls the magnitude of the resonances, while an optical phase shifter located in the optical resonator controls the spectral position of the resonances. Either the optical coupler or the optical phase shifter, or both, can be tuned to adjust the modulator's radio-frequency response curve, which can be used to improve the optical signal quality over that attainable with prior-art Mach-Zehnder-type optical modulators.

According to another embodiment, an optical modulator of the invention comprises an optical Mach-Zehnder interferometer having first and second internal arms; a first optical resonator; and a first optical coupler adapted to optically couple the first optical resonator and the first internal arm. The optical modulator is adapted to modulate an optical carrier with data applied to a data input of the modulator. The first optical resonator and the first optical coupler are controllably tunable to change radio-frequency response of the modulator to the data modulation.

According to yet another embodiment, a method for modulating light comprises the step of applying an optical carrier to an optical Mach-Zehnder interferometer having first and second internal arms. The optical Mach-Zehnder interferometer is part of an optical modulator. The optical modulator further comprises an optical resonator and an optical coupler adapted to optically couple the optical resonator and the first internal arm. The method further comprises the steps of modulating the optical carrier with data applied to a data input of the modulator; and controllably tuning the optical resonator and the optical coupler to change radio-frequency response of the modulator to the data modulation.

BRIEF DESCRIPTION OF THE DRAWINGS

Other aspects, features, and benefits of the present invention will become more fully apparent from the following detailed description, the appended claims, and the accompanying drawings in which:

Fig. 1 shows a schematic diagram of a prior-art optical modulator;

Fig. 2 graphically shows a representative radio-frequency (RF) response of the optical modulator shown in Fig. 1;

Fig. 3 graphically shows optical-domain manifestation of the RF response shown in Fig. 2;

Fig. 4A shows a schematic diagram of a waveguide circuit that can be used in the optical modulator of Fig. 1 according to one embodiment of the invention;

Figs. 4B-C show schematic diagrams of two representative embodiments of a tunable coupler used in the waveguide circuit of Fig. 4A;

5 Fig. 4D shows a Y-coupler that can be used to implement a tunable coupler used in the waveguide circuit of Fig. 4A;

Figs. 5A-F graphically show representative spectral characteristics of the waveguide circuit of Fig. 4;

10 Figs. 6A-B graphically show how the waveguide circuit of Fig. 4 can be used to produce a relatively flat optical-domain response curve for a modulator employing that waveguide circuit;

Figs. 7A-B graphically show how the waveguide circuit of Fig. 4 can be used to controllably limit the bandwidth of a modulator employing that waveguide circuit;

15 Figs. 8A-B graphically show how the waveguide circuit of Fig. 4 can be used to invert the optical-domain response curve for a modulator employing that waveguide circuit;

Fig. 9 shows a block diagram of a communication system employing the waveguide circuit of Fig. 4 according to one embodiment of the invention;

20 Fig. 10 shows a schematic diagram of a waveguide circuit that can be used in an optical modulator that is analogous to the optical modulator of Fig. 1 according to one embodiment of the invention; and

Fig. 11 shows a schematic diagram of a waveguide circuit that can be used in an optical modulator that is analogous to the optical modulator of Fig. 1 according to another embodiment of the invention.

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DETAILED DESCRIPTION

Fig. 1 shows a schematic diagram of a prior-art optical modulator **100**. Modulator **100** has a waveguide circuit **102** and a driver **104**. Waveguide circuit **102** incorporates a Mach-Zehnder interferometer (MZI), the operation of which is based on interference between two optical sub-beams. Driver **104** controls, via a control signal **106**, the relative phase shift
30 between the sub-beams and, therefore, the phase and intensity of the optical output beam produced by waveguide circuit **102**.

An optical input beam, e.g., generated by a laser (not explicitly shown in Fig. 1), is received by an input waveguide **110** of waveguide circuit **102** and split into two sub-beams by an optical splitter **120**. Each of the sub-beams then propagates through a respective one of MZI internal arms **130a-b**. The sub-beams are recombined by an optical combiner **140** and the resulting beam is directed into an output waveguide **150**.

Control signal **106** is applied to electrodes **132** of MZI arm **130a**, which creates an electric field in the material of that MZI arm. The electric field affects the material's refractive index, which in turn affects the optical phase accrued by the sub-beam in MZI arm **130a**. In contrast, the optical phase accrued by the other sub-beam in MZI arm **130b** is unaffected by control signal **106**. If the relative phase shift between the two sub-beams is 180 degrees, then the sub-beams interfere 'destructively' at optical combiner **140** such that the light does not couple into output waveguide **150** and radiates into the substrate of waveguide circuit **102**, which results in substantially no light being output from waveguide **150**. If the relative phase shift between the two sub-beams is 0 degrees, then the sub-beams interfere 'constructively' such that the light does couple into output waveguide **150** and does not substantially radiate into the substrate of waveguide circuit **102** at optical combiner **140**, which results in maximum light intensity being output from waveguide **150**. Intermediate phase shift values (e.g., between 0 and 180 degrees) result in intermediate light intensities being transmitted through waveguide circuit **102**. The phase of the output signal produced by waveguide circuit **102** is also determined by the voltage of control signal **106**.

Fig. 2 graphically shows a representative radio-frequency (RF) response of modulator **100**. More specifically, the "noisy" and smooth traces in Fig. 2 are the experimentally measured and numerically simulated RF response curves, respectively. To obtain an experimental response curve, driver **104** is first configured to apply to waveguide circuit **102** a dc bias voltage that causes the output beam to have approximately 50% of the maximum intensity. Driver **104** is then configured to superimpose a relatively small sinusoidal RF signal onto the dc bias voltage, which causes the intensity of the output beam to become RF modulated. Finally, the frequency of the sinusoidal RF signal is swept across a frequency range of interest while the amplitude of the sinusoid is being kept constant and the amplitude of the intensity modulation at the output of waveguide circuit **102** is being measured. Fig. 2 displays the measurement results on a graph, in which the horizontal and vertical axes represent the frequency of the sinusoidal

RF signal expressed in GHz and the amplitude of the optical intensity modulation expressed in dB, respectively. More details on the techniques for measuring RF responses of optical modulators similar to modulator **100** can be found, e.g., in U.S. Patent No. 7,142,309, which is incorporated herein by reference in its entirety.

5 Fig. 3 graphically shows optical-domain manifestation of the RF response shown in Fig. 2. More specifically, the relatively tall arrow located at about 193,390 GHz represents an optical carrier signal (laser line) applied to waveguide **110** of waveguide circuit **102**. RF modulation of the optical carrier signal in waveguide circuit **102** produces one or more optical-modulation sidebands at each side of the carrier. For simplicity, it is assumed here that a single
10 pair of symmetrically located sidebands is generated for a given RF modulation frequency. The relatively short arrows in Fig. 3 depict two such pairs, one pair (solid arrows) corresponding to the modulation frequency of 2.5 GHz and the other pair (dashed arrows) corresponding to the modulation frequency of 7.5 GHz. One skilled in the art will appreciate that the exact shape, or spectral content, of the optical-modulation sidebands depends on the modulation format and
15 device-implementation specifics.

Inspection of Fig. 3 reveals, for example, that increasing a frequency offset with respect to the carrier frequency from 2.5 to 7.5 GHz increases signal attenuation by about 2 dB (see also Fig. 2). When expressed in terms of spectral attenuation gradient (defined as a modulus of the slope of the response curve), this increase in attenuation corresponds to a gradient value of
20 about 0.4 dB/GHz. In general, in the process of imprinting spectral RF components of control signal **106** onto the optical output signal, waveguide circuit **102** weights those spectral components in accordance with the circuit's RF response curve. If the spectral attenuation gradient is relatively large, then the optical waveforms generated by waveguide circuit **102** can contain distortions associated with such weighting, which can disadvantageously cause the
25 optical-signal "eye" closure and/or other detrimental manifestations.

Fig. 4A shows a schematic diagram of a waveguide circuit **402** that can replace waveguide circuit **102** in optical modulator **100** according to one embodiment of the invention. Similar to waveguide circuit **102**, waveguide circuit **402** incorporates an MZI having two MZI internal arms **430a-b**. However, one difference between waveguide circuits **102** and **402** is that,
30 in the latter, MZI arm **430a** is coupled via a thermo-optic coupler **434** to an optical resonator **460**. Thermo-optic coupler **434** is tunable and is designed to control the coupling strength

between MZI arm **430a** and resonator **460**. Note that a tunable coupling means other than thermo-optic can be used for coupler **434**. Methods, such as carrier injection, carrier depletion, stress, photorefractive effects, or other techniques that enable controllable change of the effective refractive index of waveguide material(s), can be used as a physical principle of operation for thermo-optic coupler **434**.

Resonator **460** has a waveguide loop **462** and an electro-optic phase shifter **464** located in the loop. A suitable phase shifter that can be used as phase shifter **464** is disclosed, e.g., in U.S. Patent Application Publication No. 2006/0045522, which is incorporated herein by reference in its entirety. Phase shifter **464** has electrodes (not explicitly shown in Fig. 4) that act similar to electrodes **132** of waveguide circuit **102** and can be driven by control signal **106**. In addition, MZI arm **430b** incorporates a thermo-optic phase shifter **436** that can be used to adjust the relative phase difference between the optical sub-beams in MZI arms **430a-b**, e.g., when thermo-optic coupler **434** is tuned to change the coupling strength between MZI arm **430a** and resonator **460**. Furthermore, phase shifter **436** can be used to configure waveguide circuit **402** for optimal performance with various transmission formats. For example, if basic on/off keying is used, then phase shifter **436** is set to achieve about a 50% power output, or to a setting such that a minimum optical power output is attained when the modulator is in a state corresponding to an 'off' state of control signal **106**. Alternately, for a duobinary or differential phase-shift-keying format, phase shifter **436** can be set to create appropriate power output from waveguide circuit **402** for that modulation format.

Figs. 4B-C show schematic diagrams of two representative embodiments of tunable coupler **434**. Tunable coupler **434** shown in Fig. 4B has an MZI **431**, in which the operating principles described above in reference to the MZI of waveguide circuit **102** (Fig. 1) are used to control the amount of light emitted from each of output ports **433a-b**. However, in the case of MZI **431**, since there are two output ports, the light that was previously described as radiating into the substrate now substantially couples into alternate output ports **433a-b**. MZI **431** has two 50/50 directional couplers **435a-b** and a thermo-optic phase shifter **437**. The latter is similar to the above-described thermo-optic phase shifter **436**.

Fig. 4C illustrates a directional coupler approach to the implementation of tunable coupler **434**. More specifically, tunable coupler **434** of Fig. 4C has a heater **439** that is used to

change the optical coupling properties between two proximate waveguides and thus control the amount of light emitted from each of output ports **433a-b**.

Fig. 4D shows a Y-coupler **441**, two of which can be serially connected to implement tunable coupler **434**. Each of the “upper Y” branches of coupler **441** has a respective heater **439** that can controllably change the transmission characteristics through the branch. Furthermore, Y-coupler **441** can be used in circumstances where only one input waveguide and two output waveguides are needed. Such circumstances present themselves, e.g., in waveguide circuit embodiments shown in Figs. 10 and 11.

Figs. 5A-B graphically show representative loss curves for MZI arm **430a** and resonator **460**. More specifically, Fig. 5A shows a loss curve for the configuration, in which coupler **434** has been tuned and fixed to moderately couple resonator **460** to MZI arm **430a**. The moderate coupling condition can be achieved, e.g., when the coupling factor $\rho=(1-\kappa)^{0.5}$ is smaller than the field attenuation factor in the resonator $\gamma=10^{-\alpha L/20}$, where κ is the coupling coefficient of the coupler, α and L are the loss coefficient and cavity length of the resonator, respectively, such that αL represents the resonator round-trip loss expressed in dB. Fig. 5B shows a loss curve for the configuration, in which coupler **434** has been tuned and fixed to critically couple resonator **460** to MZI arm **430a**. The critical coupling condition can be achieved, e.g., when coupling factor ρ is close to field attenuation factor γ . The loss curves shown in each of Figs. 5A-B are produced in the absence of data modulation by slowly changing the wavelength of the (non-modulated, CW) optical input signal applied to waveguide circuit **402**.

The dips in the loss curves shown in Figs. 5A-B, also often referred to as spectral resonances, are caused by interference between the light making round trips through the resonator loop. The resonances are separated from one another by a frequency interval that corresponds to $1/T$, where T is the round-trip transit time in resonator **460**. The coupling strength set by coupler **434** controls the partition of light between the direct propagation path and the loop “detour” path and, therefore, determines the extent of light extinction due to the interference. In a representative embodiment of waveguide circuit **402**, coupler **434** enables the magnitude of the loss curve (the depth of the dips) to be tunable between about 0 and 30 dB.

The effective optical length of resonator **460** is determined by the physical length of loop **462**, including the coupler, the passive, and the active (phase shifter **464**) waveguide portions of the loop, multiplied by the effective optical refractive indices of each section. This includes the

optical phase accrued by the optical signal in electro-optic phase shifter **464**. A dc bias voltage applied to phase shifter **464** controls the optical phase accrued therein and therefore the spectral position of and/or the spectral separation between the resonances. Alternately, two dc biases can be applied to the coupler in a way that can control the position of the resonances. A

5 periodic driving signal, e.g., a pseudo-random bit sequence (PRBS) applied to phase shifter **464** via control signal **106**, has the effect of spectrally moving the comb of resonances in a corresponding periodic manner, e.g., as indicated by the double-headed arrows in Fig. 5B. A non-periodic driving signal, e.g., that corresponding to a random bit stream (RBS), will also move the comb of resonances, but in a non-periodic manner that reflects the specific bit
10 sequence carried by the RBS. If averaged over time, the effect of modulation-induced comb motion is to broaden the resonances and to reduce their depth.

Figs. 5C-D graphically show the effect of resonator **460** on carrier-frequency and modulation-sideband components, respectively, of an optical signal processed by waveguide circuit **402**. Loss curve **502** shown in Fig. 5C is analogous to each of the loss curves shown in
15 Figs. 5A-B. Note that loss curve **502** has a minimum at frequency ω_0 . Phase curve **504** (also shown in Fig. 5C) plots a phase shift imparted by resonator **460** onto the carrier-frequency component of optical signal **422** in the course of transforming that signal into optical signal **428** (see Fig. 4).

The data modulation imparted by phase shifter **464** causes the spectral content of optical
20 signal **428** to be different from the spectral content of optical signal **422**. More specifically, the phase modulation causes optical signal **428** to have modulation-sideband components in addition to the carrier-frequency component originally present in signal **422**. Transfer curve **512** and phase curve **514** shown in Fig. 5D characterize the amplitude and phase, respectively, of the modulation-sideband components of optical signal **428**. Note that transfer curve **512** is a
25 normalized curve. The normalization value is obtained by treating phase shifter **464** as “an effective light source” that generates an optical sideband within resonator **460** and taking the output power of that effective light source as a reference level. Thus, the value of 0 dB on the (left-side) vertical axis in Fig. 5D corresponds to a situation, in which the sideband power in optical signal **428** is the same as the sideband power generated within resonator **460**. Transfer
30 curve **512** indicates that, depending on the frequency, interference effects can either enhance or suppress the sideband power in optical signal **428** with respect to that inside resonator **460**.

Similar to loss curve **502**, transfer curve **512** is a quasi-periodic curve having a plurality of dips separated by $1/T$. However, the dips of transfer curve **512** are spectrally shifted with respect to the spectral resonances of loss curve **502** by about $1/2 T$, which aligns a maximum of transfer curve **512** with a minimum of loss curve **502**. This relative spectral alignment of curves **502** and **512** is substantially preserved even when coupler **434** and/or phase shifter **464** are being tuned or receive an RF-modulated control signal.

Figs. 5E-F graphically show the effect of data-modulation frequency (e.g., that of control signal **106**) on the sideband power in optical signal **428**. More specifically, each of Figs. 5E-F shows curves **502** and **512** (see also Figs. 5C-D) along with three vertical arrows that represent exemplary spectral components of optical signal **428**. The relatively tall arrow in the middle represents the carrier-frequency component of optical signal **428**, and the two relatively short arrows at both sides of the carrier-frequency component represent two modulation-sideband components of that optical signal. Fig. 5E corresponds to a modulation frequency of about 5 GHz, which causes each of the modulation-sideband components to be spectrally separated from the carrier-frequency component by about 5 GHz. Fig. 5F corresponds to a modulation frequency of about 20 GHz, which causes each of the modulation-sideband components to be spectrally separated from the carrier-frequency component by about 20 GHz.

The settings of coupler **434** and resonator **460** are selected so as to spectrally place the carrier frequency (labeled ω_1 in Figs. 5E-F) substantially equidistantly between two adjacent spectral resonances of loss curve **502**. This spectral placement also aligns the carrier frequency with a dip of transfer curve **512**. As already indicated above in reference to Figs. 5C-D, loss curve **502** applies to the carrier-frequency component, whereas transfer curve **512** applies to the modulation-sideband components. Inspection of Figs. 5E-F then reveals that, with the amplitude of control signal **106** being fixed, a change in the modulation frequency of the control signal from about 5 GHz to about 20 GHz causes the modulation-sideband power to change by about 8 dB. In particular, Fig. 5E indicates that, at 5 GHz, the interference effects induced by resonator **460** cause an effective power loss of about -2 dB for the modulation-sideband components of optical signal **428**. Similarly, Fig. 5F indicates that, at 20 GHz, those interference effects cause an effective power gain of about $+6$ dB for the modulation-sideband components.

If waveguide circuit **102** is replaced in modulator **100** by waveguide circuit **402**, then one can use the above-described spectral characteristics of resonator **460** to favorably modify the modulator's RF response and improve the overall quality of the optical output signal. As an example, three useful configurations of waveguide circuit **402** are described below in reference to Figs. 6A-B, 7A-B, and 8A-B, respectively. More specifically, the waveguide-circuit configuration illustrated by Figs. 6A-B helps to flatten the optical-domain response curve shown in Fig. 3. The waveguide-circuit configuration illustrated by Figs. 7A-B helps to bandwidth-limit the optical-domain response curve. The waveguide-circuit configuration illustrated by Figs. 8A-B helps to invert the optical-domain response curve. One skilled in the art will appreciate that other configurations of waveguide circuit **402** can similarly be used to achieve other desired modifications of the modulator's RF-response curve.

Figs. 6A-B graphically show how waveguide circuit **402** can be used to produce a relatively flat optical-domain response curve for a modulator employing that waveguide circuit. The results of Fig. 6 can also be viewed as illustrating a method of broadening the bandwidth. More specifically, bandwidth is often defined as the spectral width between two points corresponding to a 3-dB attenuation. Since flattening of the response curve broadens the frequency separation between the 3-dB attenuation points, it thereby increases the bandwidth.

Referring first to Fig. 6A, a dashed line **602** shows the optical-domain response curve of waveguide circuit **402** when thermo-optic coupler **434** is configured such that the coupler fully couples light to the cross state, thereby causing the light to make one complete round trip within resonator **460** and then be substantially fully coupled out of the resonator and back into MZI arm **430a**. This configuration effectively minimizes the resonator effect on the modulator response. Furthermore, response curve **602** predominantly represents the electro-optic response of the phase shifting component, i.e., phase shifter **464**. The setting of the coupler can also be tuned to increase (e.g., maximize) the resonator effect on the modulator response. Response curve **604** characterizes the modulation-sideband frequency response of MZI arm **430a** and resonator **460** in the latter configuration.

Note that the shape of response curve **602** is similar to that of the response curve shown in Fig. 3. The shape of response curve **604** substantially represents the shape of time-averaged transfer curve **512**. The effective optical length of resonator **460** is selected so that the minimum (or the center point) of a dip in response curve **604** is substantially lined up with the

laser line (optical carrier-frequency component) represented by the arrow located at about 193,390 GHz. As already indicated above in reference to Figs. 5C-F, this spectral alignment also means that the laser line is spectrally placed substantially equidistantly between two adjacent time-averaged spectral resonances of loss curve **502** (not explicitly shown in Fig. 6A).

5 Generally, one can spectrally align a resonance comb with a carrier frequency by appropriately setting the effective optical length for the optical resonator.

Referring now to Fig. 6B, a solid line **606** shows the optical-domain response curve of waveguide circuit **402** for the same coupling strength as that corresponding to response curve **604**. One skilled in the art will understand that response curve **606** is substantially a product of

10 response curves **602** and **604**. As in Fig. 3, the relatively short arrows in Fig. 6B depict two pairs of modulation sidebands, one pair (solid arrows) corresponding to the modulation frequency of 2.5 GHz and the other pair (dashed arrows) corresponding to the modulation frequency of 7.5 GHz. Note that the difference in attenuation for 2.5 and 7.5 GHz imposed by response curve **606** is now only about 0.3 dB, which corresponds to a spectral attenuation

15 gradient value of about 0.06 dB/GHz.

This relatively low value of the spectral attenuation gradient can be achieved, e.g., by appropriately tuning thermo-optic coupler **434** to find an optimal coupling strength that produces an optimal shape for response curve **604** and forces response curve **606** to attain a relatively flat shape. Intermediate coupling strengths (e.g., between 1 and the optimal coupling

20 strength) will result in intermediate spectral attenuation gradient values (e.g., between about 0.3 and 0.06 dB/GHz). Note also that, in such a configuration, the resonator is preferably designed such that the relaxation time of the resonator is faster than the spectral response components of the signal at that frequency. The relatively flat shape of response curve **606** enables the spectral RF components of control signal **106** to be more accurately imprinted onto the optical signal

25 with waveguide circuit **402** than with waveguide circuit **102**. As a result, optical waveforms generated by waveguide circuit **402** advantageously contain fewer and/or smaller distortions than optical waveforms generated by waveguide circuit **102**.

For optimal performance, certain transmission formats use a transmitter having a bandwidth that is limited to a specified frequency range. For example, low-pass filtered

30 duobinary is a transmission format that, at a bit rate of about 40 Gb/s, enables favorable performance if the transmitter has a bandwidth between about 10 and 13 GHz. In prior-art

communication systems, bandwidth limiting is often achieved by passing the electrical drive signal (such as control signal **106**, Fig. 1) through an appropriate electrical bandpass filter before applying the drive signal to a circuit analogous to waveguide circuit **102**. Alternatively, bandwidth limiting is achieved by placing an appropriate optical bandpass filter at the modulator output. Both of these prior-art bandwidth-limiting solutions disadvantageously use extra components (filters), which increases the level of complexity and cost of the corresponding optical communication system.

Figs. 7A-B graphically show how waveguide circuit **402** can be used to controllably limit the bandwidth of a modulator employing that waveguide circuit without the use of additional electrical or optical bandpass filters. Referring first to Fig. 7A, a dashed line **702** reproduces response curve **602** (see Fig. 6A). A solid line **704** has a shape corresponding to that of time-averaged transfer curve **512**. Note that the effective optical length of resonator **460** is now selected so that the laser line is located approximately at the midpoint between two adjacent dips of response curve **704**. As indicated above in reference to Figs. 5C-F, this spectral alignment also means that the laser line is spectrally aligned with one of time-averaged spectral resonances of loss curve **502** (not explicitly shown in Fig. 7A).

Referring now to Fig. 7B, a solid line **706** shows the optical-domain response curve of waveguide circuit **402** for the same coupling strength as that corresponding to response curve **704**. One skilled in the art will appreciate that response curve **706** is substantially a product of response curves **702** and **704**. Note that the bandwidth defined by response curve **706** is smaller than the bandwidth defined by response curve **702**. The extent of bandwidth reduction is controlled by the spectral separation between the dips of response curve **704** and the depth of those dips. The spectral separation between the dips can be selected by (i) selecting an appropriate physical length for waveguide loop **462** and/or (ii) tuning phase shifter **464**. For a given physical length of waveguide loop **462**, the degree of bandwidth limitation can be controllably adjusted with thermo-optic coupler **434** and/or phase shifter **464** to optimize the modulator performance for a given set of transmission-link conditions, such as the amount of residual dispersion and other transmission-link impediments. In addition, multiple resonators could be used to further shape the spectral response of the modulator.

Figs. 8A-B graphically show how waveguide circuit **402** can be used to invert the optical-domain response curve for a modulator employing that waveguide circuit. Referring

first to Fig. 8A, a dashed line **802** shows a response curve that is analogous to response curve **602** (see Fig. 6A). A solid line **804** has a shape corresponding to that of time-averaged transfer curve **512**. Note that the effective optical length of resonator **460** is selected so that the minimum (or the center point) of a dip in response curve **804** is substantially lined up with the laser line. This spectral alignment also means that the laser line is spectrally placed substantially equidistantly between two adjacent time-averaged spectral resonances of loss curve **502** (not explicitly shown in Fig. 8A).

Response curve **802** differs from response curve **602** in that it is a shallower curve, meaning that it is characterized by a smaller value of the spectral attenuation gradient. More specifically, response curve **802** has a gradient value of about 0.1 dB/GHz, as opposed to a gradient value of about 0.3 dB/GHz for response curve **602**. One skilled in the art will appreciate that, depending on the circuit implementation details and the fabrication technology, waveguide circuits might have a relatively wide variation in their optical-domain RF response and therefore exhibit different spectral-attenuation gradients. This variability can be exploited to select conditions, under which response curve **804** can be a steeper curve than response curve **802**, e.g., as shown in Fig. 8A. It can be further appreciated by one skilled in the art that, if response curve **802** had a spectral-attenuation gradient equal to that of response curve **602**, e.g., 0.3 dB/GHz, then response curve **804** could be appropriately modified to be steeper than curve **802** (and curve **602**) to effectively produce a physical circuit configuration analogous to that currently illustrated by Figs. 8A-B.

Referring now to Fig. 8B, a solid line **806** shows the optical-domain response curve of waveguide circuit **402** corresponding to response curves **802** and **804**. One skilled in the art will appreciate that response curve **806** is substantially a product of response curves **802** and **804**. Note that, because response curve **804** is steeper than response curve **802**, response curve **806** is an inverted optical-domain response curve. The term “inverted” should be read here to mean that the sideband attenuation generally decreases with an increase of the modulation frequency (or the spectral separation from the carrier frequency). Recall that the optical-domain response curve of waveguide circuit **102** is characterized by sideband attenuation that generally increases with an increase of the modulation frequency. The results shown in Figs. 8A-B indicate that waveguide circuit **402** can be used in effect to overcompensate the radio-frequency roll-off inherent to the optical modulator itself. The “excess” compensation then can be used,

e.g., to at least partially compensate the RF-frequency roll-off produced by communication-system elements external to the optical modulator having waveguide circuit **402**.

Fig. 9 shows a block diagram of a communication system **900** employing waveguide circuit **402** according to one embodiment of the invention. A CW laser **910** provides a carrier-frequency signal for waveguide circuit **402**. An RF amplifier **930** uses a multiplexed data signal **928** generated by a data multiplexer (MUX) **920** to generate data-modulated control signal **106**. Waveguide circuit **402** modulates the carrier-frequency signal as described above and launches a resulting modulated optical signal **938** toward an optical receiver **990**. En route to receiver **990**, optical signal **938** might traverse one or more instances of some or all of the following elements: an optical MUX filter **940**, a long-haul optical transmission fiber **945**, an add-drop module **950**, and an optical de-MUX filter **960**. An optical-to-electrical (O/E) converter **970** of receiver **990** converts the received optical signal into a corresponding electrical signal **978**, which is then processed by a trans-impedance amplifier **980**.

Some or all of data MUX **920**, RF amplifier **930**, optical MUX filter **940**, add-drop module **950**, optical de-MUX filter **960**, O/E converter **970**, and trans-impedance amplifier **980** might have bandwidth limitations. These bandwidth limitations typically manifest themselves, e.g., as a radio-frequency roll-off qualitatively similar to that shown in Fig. 3. Advantageously, waveguide circuit **402** can be used to mitigate the detrimental affects of these bandwidth limitations. For example, waveguide circuit **402** can be configured as described above in reference to Figs. 8A-B to post-compensate the radio-frequency roll-off imposed by data MUX **920** and/or RF amplifier **930** so that the composite RF response of the optical modulator formed by the waveguide circuit, the data MUX, and the RF amplifier is substantially flat over a relatively wide spectral interval or is characterized by a relatively small spectral attenuation gradient, e.g., similar to that corresponding to response curve **606** shown in Fig. 6B. Alternatively or in addition, waveguide circuit **402** can be configured as described above in reference to Figs. 8A-B to pre-compensate the radio-frequency roll-off imposed by one or more of optical MUX filter **940**, add-drop module **950**, optical de-MUX filter **960**, O/E converter **970**, and trans-impedance amplifier **980**. One skilled in the art will appreciate that this post-compensation and/or pre-compensation is advantageously capable of reducing the number of decoding errors at receiver **990**.

One skilled in the art will appreciate that communication system **900** might include optical switches for rerouting optical signal **938** to a different receiver (not explicitly shown in Fig. 9) analogous to receiver **990**. This rerouting is likely to change the radio-frequency roll-off imposed onto optical signal **938** en route to that different receiver. In this situation, waveguide circuit **402** can be re-configured so that the pre-compensation imposed by it matches the radio-frequency roll-off corresponding to the new destination. In general, waveguide circuit **402** can be dynamically reconfigured to have the bandwidth characteristics that are most advantageous for the current routing configuration.

In one embodiment, waveguide circuit **402** can be used in a wavelength-division-multiplexing (WDM) communication system to generate a communication signal, e.g., an add signal, corresponding to one of the (idle or dropped) WDM channels. Optical communication signals corresponding to other WDM channels are usually characterized by a particular level and/or type of signal distortion. The control over the RF-response enabled by waveguide circuit **402** and exemplified by Figs. 6-8 can then be used to (pre)distort, in a controllable manner, the added signal so as to substantially match the existing-channel distortion. As a result, all signals in the WDM multiplex can have similar signal characteristics independent of the add/drop function, which enables the communication system to process the whole WDM multiplex in a uniform and consistent manner.

Fig. 10 shows a schematic diagram of a waveguide circuit **1002** that can be used in an optical modulator that is analogous to optical modulator **100** according to one embodiment of the invention. Waveguide circuit **1002** is generally analogous to waveguide circuit **402** (Fig. 4), and analogous elements of the two circuits are designated with labels having the same last two digits. In the description that follows, differences in the structure and operation of these two waveguide circuits are explained in more detail.

Referring to both Figs. 4 and 10, instead of an optical splitter **420** used in waveguide circuit **402**, waveguide circuit **1002** employs a thermo-optic coupler **1020**. As a result, either one of waveguides **1010a-b** can serve as an input waveguide for waveguide circuit **1002**. In addition, thermo-optic coupler **1020** enables operational adjustments to light distribution between MZI internal arms **1030a-b** for optimal performance. For similar reasons, waveguide circuit **1002** also employs a thermo-optic coupler **1040** instead of an optical combiner similar to

an optical combiner **440** used in waveguide circuit **402**. Note that similar thermo-optic couplers can be used in waveguide circuit **402**.

Each of MZI arms **1030a-b** is coupled via a respective thermo-optic coupler **1034** to a respective optical resonator **1060**. One purpose of coupling a separate optical resonator to each MZI arm is to reduce the amount of chirp in the output signal generated by waveguide circuit **1002** compared to that in the output signal generated by waveguide circuit **402**. In a representative configuration, control signals **1006a-b** drive phase shifters **1064a-b**, respectively, in an opposite sense to achieve a push-pull type of operation, which results in an output signal having advantageously low chirp. Additional details on push-pull operation of Mach-Zehnder modulators can be found, e.g., in U.S. Patent Application Publication Nos. 2003/0175036 and 2004/0165893, both of which are incorporated herein by reference in their entirety. The physical mechanism of chirp reduction is explained in detail, e.g., in commonly owned U.S. Patent Application Serial No. 11/684,625 filed on Mar. 11, 2007 and entitled "Semiconductor Optical Modulator," which is also incorporated herein by reference in its entirety.

Fig. 11 shows a schematic diagram of a waveguide circuit **1102** that can be used in an optical modulator that is analogous to optical modulator **100** according to another embodiment of the invention. Waveguide circuit **1102** is generally analogous to waveguide circuit **1002** (Fig. 10), and analogous elements of the two circuits are designated with labels having the same last two digits. However, one difference between waveguide circuits **1002** and **1102** is that each of MZI internal arms **1130a-b** in the latter is coupled via two thermo-optic couplers **1134** to two respective optical resonators **1160**. Using an additional optical resonator for each of MZI arms **1130a-b** is beneficial, for example, when electro-optic phase shifters **1164** are implemented in a technology (e.g., carrier depleted Si-waveguide technology) that enables the refractive index to be tuned within a relatively narrow range. This relatively narrow range imposes a corresponding limit on the phase values accessible with each electro-optic phase shifter **1164**. Concatenation of multiple resonators **1160** in each MZI arm **1130** effectively adds up the phase ranges of individual electro-optic phase shifters **1164**, thereby advantageously broadening the accessible phase range. In addition, each of electro-optic phase shifters **1164** can be configured to operate relatively close to the minimum of a selected resonance of the corresponding resonator **1160**, where its phase shifting ability (i.e., phase change per unit voltage change) is resonantly enhanced and has an advantageously large value. The latter can be used to reduce

the driving voltage applied to each of phase shifters **1164**. Furthermore, coupling multiple resonators **1160** to each MZI arm **1130** enables more flexibility in the control of the shape of the electro-optic response curve compared to that available with just one resonator being coupled to each MZI arm.

5 While this invention has been described with reference to illustrative embodiments, this description is not intended to be construed in a limiting sense. For example, a modulator of the invention can be implemented as an integrated circuit having both a waveguide circuit (e.g., one of circuits **402**, **1002**, and **1102**) and a driver (e.g., driver **104**). Each MZI arm in a waveguide circuit of the invention can be optically coupled to three or more optical resonators. For
10 asymmetric bandwidth limiting (or inversion), adjacent resonances can be placed asymmetrically with respect to the optical carrier. Each or one of splitter **420** and combiner **440** can be replaced by tunable couplers, e.g., similar to coupler **434**. Each or one of couplers **1020**, **1120**, **1040**, and **1140** can be replaced by tunable waveguide splitters/combiners, e.g., similar to splitter **420** and combiner **440**. Although embodiments of the invention have been described in
15 reference to a configuration, in which a phase shifter (e.g., phase shifter **464**) receives a data-modulated drive signal, waveguide circuits of the invention can also be configured so that an optical coupler (e.g., optical coupler **434**) receives a data-modulated drive signal. The optical coupler may receive a data-modulated drive signal in addition to or instead of the phase shifter. Various modifications of the described embodiments, as well as other embodiments of the
20 invention, which are apparent to persons skilled in the art to which the invention pertains are deemed to lie within the principle and scope of the invention as expressed in the following claims.

Unless explicitly stated otherwise, each numerical value and range should be interpreted as being approximate as if the word "about" or "approximately" preceded the value of the value
25 or range.

It will be further understood that various changes in the details, materials, and arrangements of the parts which have been described and illustrated in order to explain the nature of this invention may be made by those skilled in the art without departing from the scope of the invention as expressed in the following claims.

30 It should be understood that the steps of the exemplary methods set forth herein are not necessarily required to be performed in the order described, and the order of the steps of such

methods should be understood to be merely exemplary. Likewise, additional steps may be included in such methods, and certain steps may be omitted or combined, in methods consistent with various embodiments of the present invention.

5 Reference herein to "one embodiment" or "an embodiment" means that a particular feature, structure, or characteristic described in connection with the embodiment can be included in at least one embodiment of the invention. The appearances of the phrase "in one embodiment" in various places in the specification are not necessarily all referring to the same embodiment, nor are separate or alternative embodiments necessarily mutually exclusive of other embodiments. The same applies to the term "implementation."

10 Throughout the detailed description, the drawings, which are not to scale, are illustrative only and are used in order to explain, rather than limit the invention. The use of terms such as height, length, width, top, bottom, is strictly to facilitate the description of the invention and is not intended to limit the invention to a specific orientation.

15 Also for purposes of this description, the terms "couple," "coupling," "coupled," "connect," "connecting," or "connected" refer to any manner known in the art or later developed in which energy is allowed to be transferred between two or more elements, and the interposition of one or more additional elements is contemplated, although not required.

CLAIMS

What is claimed is:

1. An optical modulator, comprising:
 - 5 an optical Mach-Zehnder interferometer having first and second internal arms;
a first optical resonator; and
a first optical coupler adapted to optically couple the first optical resonator and the first
internal arm, wherein:
the optical modulator is adapted to modulate an optical carrier with data applied to a
10 data input of the modulator; and
the first optical resonator and the first optical coupler are tunable to change a radio-
frequency response of the modulator to the data modulation to cause
the optical modulator to exhibit an inverted radio-frequency response in a spectral range
around an optical frequency of the optical carrier.
- 15 2. The invention of claim 1, wherein:
optical loss induced in the first arm by the first optical resonator is characterized by a
spectral resonance; and
the first optical coupler is tunable to control a magnitude of said resonance.
- 20 3. The invention of claim 1, wherein the first optical resonator and the first optical coupler
have been tuned to cause the modulator to exhibit a radio-frequency response
characterized by a spectral attenuation gradient smaller than about 0.3 dB/GHz.
- 25 4. The invention of claim 1, wherein the first optical resonator comprises a tunable phase
shifter adapted to define effective optical length of said optical resonator based on a
received dc control voltage.
- 30 5. The invention of claim 4, wherein the phase shifter is further adapted to receive an
electrical radio-frequency signal to produce the data modulation.

6. The invention of claim 4, wherein:

the first optical resonator comprises a waveguide loop connected to the first optical coupler; and

the phase shifter is part of said waveguide loop.

5

7. The invention of claim 4, wherein:

optical loss induced in the first arm by the first optical resonator is characterized by one or more spectral resonances, each having a spectral position; and

the tunable phase shifter is adapted to controllably change at least one of said spectral positions.

10

8. The invention of claim 1, further comprising a second optical resonator optically coupled to the second internal arm via a second optical coupler, wherein the second optical resonator and the second optical coupler are controllably tunable to further change the radio-frequency response.

15

9. The invention of claim 1, comprising a plurality of optical resonators, each optically coupled to a respective one of the first and second internal arms via a respective tunable optical coupler, wherein at least one of the first and second internal arms is optically coupled to at least two of said optical resonators.

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10. The invention of claim 1, wherein the first optical resonator and the first optical coupler have been tuned to cause the modulator to exhibit said inverted radio-frequency response.

25

11. The invention of claim 1, wherein:

the optical modulator is part of a communication system having one or more bandwidth-limiting components external to the optical modulator; and

characteristics of said inverted response at least partially offset radio-frequency roll-off produced by said one or more bandwidth-limiting components.

30

12. The invention of claim 11, wherein:

the optical modulator is located upstream from said one or more bandwidth-limiting components; and

5 said inverted response at least partially pre-compensates the radio-frequency roll-off to mitigate its effects on signal reception at an optical receiver that is optically coupled to the modulator via said one or more bandwidth-limiting components.

13. The invention of claim 1, wherein at least one of the first and second arms comprises a respective tunable phase shifter adapted to configure the modulator for a selected modulation format.

14. The invention of claim 1, further comprising:

a second tunable optical coupler adapted to couple light from one or more input waveguides into the first and second internal arms; and

15 a third tunable optical coupler adapted to couple light from the first and second internal arms into one or more output waveguides, wherein the modulator is implemented as an integrated waveguide circuit.

15. A method of modulating light, comprising:

20 applying an optical carrier to an optical Mach-Zehnder interferometer having first and second internal arms, wherein:

the optical Mach-Zehnder interferometer is part of an optical modulator;

the optical modulator further comprises an optical resonator and an optical coupler adapted to optically couple the optical resonator and the first internal arm;

25 the optical resonator comprises a tunable phase shifter; and

optical loss induced in the first arm by the optical resonator is characterized by one or more spectral resonances, each having a spectral position;

modulating the optical carrier with data applied to a data input of the modulator, wherein the data modulation causes said spectral positions to vary in time; and

30 tuning the optical resonator and the optical coupler to change radio-frequency response of the modulator to the data modulation, wherein said tuning causes:

a time-averaged spectral resonance to be substantially at an optical frequency of the optical carrier; or
an optical frequency of the optical carrier to be spectrally located substantially equidistantly between two adjacent time-averaged spectral resonances.

5

16. The invention of claim 15, wherein:

said tuning causes the time-averaged spectral resonance to be substantially at the optical frequency of the optical carrier.

10

17. The invention of claim 15, wherein:

said tuning causes the optical frequency of the optical carrier is to be spectrally located substantially equidistantly between said two adjacent time-averaged spectral resonances.

15

18. A method of modulating light, comprising:

applying an optical carrier to an optical Mach-Zehnder interferometer having first and second internal arms, wherein:

the optical Mach-Zehnder interferometer is part of an optical modulator; and

the optical modulator further comprises an optical resonator and an optical coupler

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adapted to optically couple the optical resonator and the first internal arm;

modulating the optical carrier with data applied to a data input of the modulator; and

tuning the optical resonator and the optical coupler to cause the optical modulator to

exhibit an inverted radio-frequency response in a spectral range around an optical frequency of the optical carrier.

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19. The invention of claim 18, wherein:

the optical modulator is part of a communication system having one or more bandwidth-limiting components external to the optical modulator; and

the method further comprises selecting characteristics of said inverted radio-frequency

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response to at least partially offset radio-frequency roll-off produced by said one or more bandwidth-limiting components.

20. The invention of claim 19, wherein:

the optical modulator is located upstream from said one or more bandwidth-limiting components; and

5 said inverted radio-frequency response at least partially pre-compensates the radio-frequency roll-off to mitigate its effects on signal reception at an optical receiver that is optically coupled to the modulator via said one or more bandwidth-limiting components.