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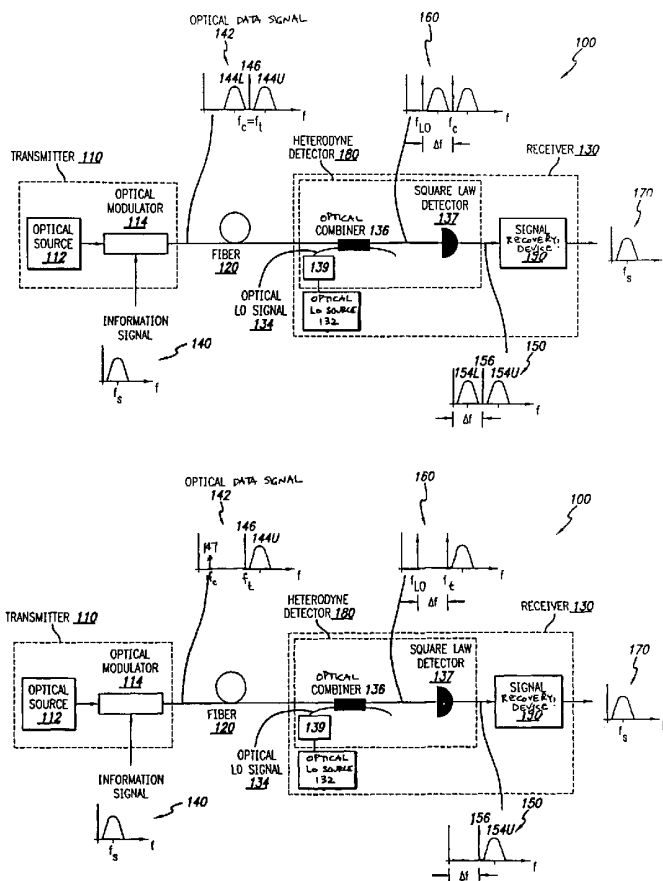
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[Continued on next page]

(54) Title: FIBER OPTIC COMMUNICATIONS



(57) **Abstract:** In a fiber optic communications system, bandwidth/frequency bands are used and allocated judiciously in order to reduce unwanted effects, such as interference from higher order harmonics or the introduction of spurious noise sources.



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## **FIBER OPTIC COMMUNICATIONS**

### **CROSS-REFERENCE TO RELATED APPLICATIONS**

[0001] This application is a continuation-in-part of pending U.S. Patent Application Serial No. 09/918,886, "Optical Communications System Using Multiplexed Single Sideband Transmission and Heterodyne Detection", by Ting K. Yee et al., filed July 30, 2001, which is a continuation-in-part of pending U.S. Patent Application Serial No. 09/728,373, "Optical Communications System Using Heterodyne Detection", by Ting K. Yee and Peter H. Chang, filed November 28, 2000, which is a continuation-in-part of pending U.S. Patent Application Serial No. 09/474,659, "Optical Communications System Using Heterodyne Detection", by Ting K. Yee and Peter H. Chang, filed December 29, 1999.

[0002] This application claims priority under 35 U.S.C. § 119(e) to U.S. Provisional Patent Application Serial No. 60/265,251, "Fiber Optic Communications Using Optical Single Sideband Transmission Including using Interleaver Filters and Heterodyne Detection and Apparatus for Impairment Compensation using Nonlinear Phase Conjugation," by Ting K. Yee, et al., filed January 30, 2001, which subject matter is incorporated herein by reference.

[0003] This application relates to pending U.S. Patent Application Serial No. 09/746,261, "Wavelength-Locking of Optical Sources," by Shin-Sheng Tarng, et al., filed December 20, 2000 and to pending U.S. Patent Application Serial No. xx/xxx,xxx, "Bidirectional Optical Transceiver Using Heterodyne Detection and a Shared Laser Source," by Anthony W. Jorgenson et al., filed on even date herewith.

[0004] The subject matter of all of the foregoing applications is incorporated herein by reference.

## BACKGROUND OF THE INVENTION

### 1. Field of the Invention

[0005] This invention relates generally to optical fiber communications.

### 2. Description of the Related Art

[0006] As the result of continuous advances in technology, particularly in the area of networking, there is an increasing demand for communications bandwidth. For example, the growth of the Internet, home office usage, e-commerce and other broadband services is creating an ever-increasing demand for communications bandwidth. Upcoming widespread deployment of new bandwidth-intensive services, such as xDSL, will only further intensify this demand. Moreover, as data-intensive applications proliferate and data rates for local area networks increase, businesses will also demand higher speed connectivity to the wide area network (WAN) in order to support virtual private networks and high-speed Internet access. Enterprises that currently access the WAN through T1 circuits will require DS-3, OC-3, or equivalent connections in the near future. As a result, the networking infrastructure will be required to accommodate greatly increased traffic.

[0007] Optical fiber is a transmission medium that is well-suited to meet this increasing demand. Optical fiber has an inherent bandwidth which is much greater than metal-based conductors, such as twisted pair or coaxial cable. There is a significant installed base of optical fibers and protocols such as SONET have been developed for the transmission of data over optical fibers. Typical communications system based on optical fibers include a transmitter, an optical fiber, and a receiver. The transmitter converts the data to be communicated into an optical form and transmits the resulting optical signal across the optical fiber to the receiver. The receiver recovers the original data from the received optical signal. Recent advances in transmitter and receiver technology have also resulted in improvements, such as increased bandwidth utilization, lower cost systems, and more reliable service.

[0008] In addition, fiber optic systems are often bidirectional. As a result, equipment is often based on transceivers, which are capable of both transmitting and receiving data, rather than stand-alone transmitters or stand-alone receivers. A transceiver combines a transmitter and a receiver or even multiple transmitter-receiver pairs. Transmitters and receivers may use the same components, although possibly for different purposes. As a result, it would be beneficial to design transceivers which share common components and therefore operate with a reduced number of these components.

[0009] Optical fiber systems also suffer from drawbacks which limit their performance and/or utility. For example, optical fibers typically exhibit dispersion, meaning that signals at different frequencies travel at different speeds along the fiber. More importantly, if a signal is made up of components at different frequencies, the components travel at different speeds along the fiber and will arrive at the receiver at different times and/or with different phase shifts. As a result, the components may not recombine correctly at the receiver, thus distorting or degrading the original signal. In fact, at certain frequencies, the dispersive effect may result in destructive interference at the receiver, thus effectively preventing the transmission of signals at these frequencies. Dispersion effects may be compensated by installing special devices along the fiber specifically for this purpose. However, the additional equipment results in additional power loss (e.g., insertion loss) as well as in additional cost, and different compensators will be required for different types and lengths of fiber. Other fiber effects, such as fiber nonlinearities, can similarly degrade performance.

[0010] As another example, the transmitter in an optical fiber system typically includes an optical source, such as a laser, and an external modulator, such as a Mach-Zender modulator (MZM). The source generates an optical carrier and the modulator is used to modulate the optical carrier with the data to be communicated. In many applications, linear modulators are preferred in order to increase the performance of the overall system. MZMs, however, are inherently nonlinear devices. Linear operation is approximated by biasing the MZM at its quadrature point and then limiting operation of the MZM to a small range around the quadrature point, thus reducing the effect of the MZM's nonlinearities. However, this results in an optical signal with a large carrier (which contains no information) and a small modulated signal (which contains the data to be

communicated). A larger optical signal to noise ratio is required to compensate for the large carrier.

[0011] As a final example, optical fibers have an inherently large bandwidth available for the transmission of data, but constructing transmitters and receivers which can take advantage of this large bandwidth can be problematic. First, current approaches, such as the on-off keying and time-division multiplexing of signals used in the SONET protocols, cannot be extended to higher speeds in a straightforward manner. This is because current electronics technology limits the speeds at which these approaches can be implemented and electronics fundamentally will not have sufficient bandwidth to fill the capacity of a fiber. Even if this were not a limitation, current modulation schemes such as on-off keying are not spectrally efficient; more data can be transmitted in less bandwidth by using more efficient modulation schemes.

[0012] Current optics technology also prevents the full utilization of a fiber's capacity. For example, in wavelength division multiplexing, signals are placed onto optical carriers of different wavelengths and all of these signals are transmitted across a common fiber. However, the components which combine and separate the different wavelength signals currently place a lower limit on the spacing between wavelengths, thus placing an upper limit on the number of wavelengths which may be used. This also leads to inefficient utilization of a fiber's bandwidth.

[0013] The ever-increasing demand for communications bandwidth further aggravates many of the problems mentioned above. In order to meet the increasing demand, it is desirable to increase the data rate of transmission across each fiber. However, this typically can only be achieved by either increasing the bandwidth being utilized and/or by increasing the spectral efficiency of the encoding scheme. Increasing the bandwidth, however, aggravates frequency-dependent effects, such as dispersion. Increasing the spectral efficiency increases the signal to noise requirements.

[0014] Thus, there is a need for optical communications systems which more fully and/or more intelligently utilize the available bandwidth of optical fibers. There is further a need to reduce or eliminate the deleterious effects caused by fiber dispersion, to reduce the

power contained in the optical carrier, and to combat the many additional drawbacks mentioned above.

### SUMMARY OF THE INVENTION

**[0015]** In one aspect of the invention, a method for generating a composite optical signal having a bandwidth of approximately  $X$  includes the following. A first electrical signal with a bandwidth of  $X/2$  is received and used to modulate a first optical carrier to generate a first optical data signal. The first optical data signal includes a sideband corresponding to the first electrical signal. The sideband is located at an offset of  $X/2$  to  $X$  from the first optical carrier. Similarly, a second electrical signal with a bandwidth of  $X/2$  is received and used to modulate a second optical carrier to generate a second optical data signal. The second optical data signal includes a sideband corresponding to the second electrical signal. The sideband is located at an offset of  $X/2$  to  $X$  from the second optical carrier. The first optical carrier and the second optical carrier are located at different frequencies. The first optical data signal and the second optical data signal are combined to generate a composite optical signal with a bandwidth of approximately  $X$  and containing the sideband of the first optical data signal and the sideband of the second optical data signal.

**[0016]** For example, in one embodiment,  $X$  is approximately 40 GHz. Each of the sidebands in the optical data signals is then located at an offset of 20-40 GHz from its respective optical carrier. In one implementation, the data is QPSK modulated and the 40 GHz composite optical signal carries an aggregate data rate of approximately 40 Gbps. In another implementation, the first optical data signal and the second optical data signal are orthogonally polarized.

**[0017]** In another aspect of the invention, a method for receiving an optical data signal includes the following. The optical data signal includes a component containing data. The optical data signal is received and mixed with an optical local oscillator signal, recovering the component using heterodyne detection. The recovered component occupies less than one octave of frequency.

[0018] In another aspect of the invention, a method for receiving an optical data signal includes the following. The optical data signal includes a single sideband located at a frequency offset of  $+\Delta f$  with respect to an optical local oscillator signal. The optical data signal is optically filtered to attenuate noise located at a frequency offset of  $-\Delta f$  with respect to the optical local oscillator signal. The filtered optical data signal is then detected.

[0019] In another aspect of the invention, a first optical data signal containing first data is generated and a second optical data signal containing second data is also generated. The two optical data signals are optically combined to generate a composite optical signal. The composite optical signal is to be used in an optical system that has predefined frequency bands for transmission but only occupies a single one of the predefined frequency bands. In one embodiment, the predefined frequency bands are defined by a standard such as the ITU grid. The two optical data signals may be symmetrically disposed about a center frequency in the frequency band.

[0020] Other aspects of the invention include devices, systems and protocols for implementing the methods described above.

[0021] Another aspect of the invention provides a transceiver with a reduced number of laser sources. In particular, a shared laser source is used to generate a source beam for an optical transmitter and a local oscillator beam for a corresponding heterodyne receiver, thus using only one laser source rather than two separate laser sources.

[0022] In one implementation, a transceiver includes at least one transmitter-receiver pair. The transmitter-receiver pair includes a laser source, an optical splitter, an optical transmitter and a heterodyne receiver. The laser source generates a laser beam, which is split by the optical splitter into two parts: a source beam and a local oscillator beam. On the transmit side, the optical transmitter modulates the source beam with an incoming electrical data signal, thus generating an outgoing optical data signal. On the receive side, the heterodyne receiver uses the local oscillator beam as an optical local oscillator in a heterodyne detection process to recover an electrical data signal from an incoming optical data signal.

[0023] The wavelength of the laser beam from the laser source may be fixed in a number of different ways. In one implementation, the wavelength of the laser beam is locked without using a laser beam received from another transceiver. For example, the wavelength could be locked to a fixed reference, such as determined by the spectral response of an etalon. In another implementation, the wavelength of the laser beam is locked with the incoming optical data signal, for example to maintain a frequency offset used in the heterodyne detection.

[0024] In another embodiment, the transceiver includes two (or more) transmitter-receiver pairs and an optical combiner. The optical combiner combines the optical data signals generated by the optical transmitters in the transmitter-receiver pairs. For example, each optical transmitter might generate an optical data signal at a different wavelength, with the optical combiner combining the signals on a wavelength division multiplexing basis. Alternately, each optical transmitter might generate an optical data signal with a different polarization, with the optical combiner combining the signals on a polarization division multiplexing basis.

[0025] In another aspect of the invention, a bidirectional optical communications system includes two transceivers, such as those described above. Each transceiver has an optical data input and an optical data output, and the optical data output of each transceiver is coupled to the optical data input of the other transceiver.

[0026] In one implementation, one of the transceivers is a master transceiver and the other transceiver is a slave transceiver. The transmitter-receiver pairs in the slave transceiver include a wavelength locking device which wavelength locks the laser beam generated by that transmitter-receiver pair with the optical data signal received by that transmitter-receiver pair (from the corresponding transmitter-receiver pair in the master transceiver). The master/slave roles can be determined in any number of ways. For example, the transceivers can be manually configured to function as either master or slave. Alternately, the transceivers can negotiate which is master and which is slave.

[0027] Other aspects of the invention include methods relating to the devices described above.

BRIEF DESCRIPTION OF THE DRAWING

[0028] The invention has other advantages and features which will be more readily apparent from the following detailed description of the invention and the appended claims, when taken in conjunction with the accompanying drawing, in which:

[0029] FIGS. 1A-1B are block diagrams of unidirectional fiber optic communications systems using heterodyne detection.

[0030] FIG. 2 is a block diagram of one embodiment of a signal recovery device based on squaring a signal containing a tone and a sideband.

[0031] FIG. 3 is a block diagram of another embodiment of a signal recovery device based on multiplying a tone with a sideband.

[0032] FIG. 4 is a diagram of one embodiment of a transmitter using pilot tones.

[0033] FIG. 5 is a block diagram of a bidirectional fiber optic communications system.

[0034] FIG. 6A is a block diagram of a device for wavelength locking a laser source to a fixed reference frequency.

[0035] FIG. 6B is the spectral response of an etalon used in the wavelength-locking device of FIG. 6A.

[0036] FIG. 7 is a block diagram of a device for wavelength locking a laser source relative to another optical beam.

[0037] FIG. 8A is a flow diagram illustrating one method of determining master/slave roles.

[0038] FIG. 8B is a flow diagram illustrating one method of negotiating master/slave roles.

[0039] FIG. 9 is a block diagram of another bidirectional fiber optic communications system.

[0040] FIG. 10 is a block diagram of yet another bidirectional fiber optic communications system.

[0041] FIG. 11 is a partial block diagram of yet another bidirectional fiber optic communications system.

[0042] FIG. 12 is a block diagram of one embodiment of signal recovery device 190.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0043] FIG. 1A is a block diagram of a unidirectional fiber optic communications system 100 using heterodyne detection. System 100 includes a transmitter 110 coupled to a receiver 130 by optical fiber 120. System 100 is used to transmit an information signal from transmitter 110 to receiver 130 via fiber 120. Transmitter 110 includes an optical source 112 coupled to an optical modulator 114. Examples of optical sources include solid state lasers and semiconductor lasers. Example optical modulators 114 include Mach Zender modulators, electro-optic modulators, and electro-absorptive modulators. Receiver 130 includes a heterodyne detector 180 coupled to a signal recovery device 190. It also includes a source 132 for generating an optical local oscillator signal 134 for use in the heterodyne detector 180. Examples of optical LO source 132 include solid state lasers and semiconductor lasers.

[0044] System 100 operates as follows. The frequency spectrum of an example information signal is shown by spectrum 140, which is characterized by a frequency  $f_s$ . The frequency  $f_s$  could be zero, for example, if the information signal is based on on-off keying. The information signal 140 may be any of a variety of signals. For example, it may be a single high speed data stream. Alternately, it may contain a number of data streams which are time-division multiplexed together, for example, if 64 OC-3 data streams are combined together to form a single 10 Gbps signal, which serves as the information signal 140. As another example, the information signal may include a number of constituent signals, each

of which occupies a different frequency band within spectrum 140. In other words, the constituent signals may be frequency division multiplexed together. Other types of information signals 140 and methods for combining constituent signals to form the information signal 140 will be apparent.

[0045] Transmitter 110 receives the information signal 140 and generates an optical data signal 142. Optical signal 142 is characterized by a carrier frequency  $f_c$  and includes at least one sideband 144 based on the information signal 140 and at least one tone 146, shown at a frequency  $f_t$  in the following examples. Various techniques may be used to achieve this function.

[0046] In more detail, the optical source 112 produces an optical carrier signal at the carrier frequency  $f_c$ . The modulator 114 receives the information signal 140 and modulates the optical carrier with the information signal 140 to generate optical data signal 142. In the example of FIG. 1A, double sideband modulation is illustrated, resulting in upper sideband 144U and lower sideband 144L which are centered about the carrier frequency  $f_c$ . Other types of modulation, such as single sideband modulation, could also be used. In a preferred embodiment, one of the sidebands 144 is substantially attenuated with respect to the other sideband. Continuing this example, the modulator 114 also produces a significant signal at the carrier frequency  $f_c$ , which serves as a tone 146.

[0047] In a preferred embodiment, the modulator 114 includes a Mach-Zender modulator (MZM). The conventional two-arm MZM has a raised cosine transfer function. In one approach, the MZM is biased at a quadrature point of the transfer function. The raised cosine transfer function may then be used to approximate a linear transfer function, particularly if the modulator 114 is operated over a limited range around the quadrature point. When operated in this fashion, the modulator 114 generates dual sidebands 144L and 144U and a large carrier 146, which may be used as a tone.

[0048] In a different approach, the optical modulator 114 is a conventional modulator including two or more arms. Two of the arms form a conventional MZM and information signal 140 modulates the signal in these two arms. However, the MZM formed by the two arms is not biased at one of the quadrature points. Rather, it is biased at one of the

extremum points of the raised cosine transfer function. The result is an optical data signal which includes two sidebands 144L and 144U but no optical carrier at  $f_c$  since operation at the extremum point suppresses the carrier. The modulator may include a third arm, which is used to reintroduce the optical carrier 146, preferably in a controlled manner by adjusting both the amplitude and phase of the carrier. The reintroduced carrier then functions as a tone in optical signal 142. This approach is advantageous compared to a MZM biased at its quadrature point because the amplitude and phase of the optical carrier may be tailored for different purposes. In one embodiment, since the optical carrier 146 does not carry any information, the amplitude of carrier 146 is minimized to reduce wasted power.

[0049] In another approach, a conventional two-arm MZM is biased at a point close to but slightly offset from the extremum point of the raised cosine transfer function. The slight offset results in some carrier being introduced into the optical signal, thus resulting in a spectrum with a reduced optical carrier.

[0050] Returning to FIG. 1A, the optical data signal 142 is transmitted over fiber 120 to receiver 130. Current optical fibers have two spectral regions which are commonly used for communications: the 1.3 and 1.55 micron regions. At a wavelength of 1.3 micron, transmission of the optical signal is primarily limited by attenuation in the fiber 120. Dispersion is less of a factor. Conversely, at a wavelength of 1.55 micron, the optical signal will experience more dispersion but less attenuation. Hence, the optical signal preferably has a wavelength either in the 1.3 micron region or the 1.55 micron region and, for long distance communications systems, the 1.55 micron region is generally preferred.

[0051] At receiver 130, heterodyne detector 180 receives the incoming optical data signal 142 and also receives an optical local oscillator signal 134 at a frequency  $f_{LO}$  from a LO source 132. In FIG. 1A, the local oscillator signal 134 is shown at a frequency  $f_{LO}$  which is lower than the carrier frequency  $f_c$ , but the local oscillator signal 134 may also be located at a frequency  $f_{LO}$  which is higher than the carrier frequency  $f_c$ . The optical signal 142 and local oscillator signal 134 are combined and heterodyne detection of the combined signal effectively downshifts the optical signal 142 from a carrier at frequency  $f_c$  to a frequency  $\Delta f$ , which is the difference between the local oscillator frequency  $f_{LO}$  and the carrier frequency  $f_c$ . The resulting electrical signal has spectrum 150. Note that both

sidebands 154L and 154U and tone 156 have also been frequency downshifted compared to optical signal 142.

[0052] Signal recovery device 190 mixes at least one of the sidebands 154 with one of the tones 156 to produce a number of frequency components, including one frequency component 170 located at the difference frequency  $\Delta f$  between the relevant sideband 154 and tone 156. This difference component 170 contains the information signal 140, although it may be offset in frequency from the original frequency  $f_s$ , depending on the frequencies of the sideband 154 and tone 156. Frequency components other than the difference component 170 may be used to recover the information signal. For example, the mixing typically also produces a sum component located at the sum of the frequencies of the relevant sideband 154 and tone 156, and the information signal 140 may be recovered from this sum component rather than the difference component. If more than one sideband 154 is processed by signal recovery device 190, each sideband 154 preferably is processed separately from the others in a manner which prevents destructive interference between the sidebands.

[0053] Recovering the information signal 140 based on the difference component of sideband 154 and tone 156 is advantageous because it can result in noise cancellation. For example, sideband 154L and tone 156 are affected similarly by laser phase noise produced by optical source 112 and optical local oscillator source 132. Using the difference component can effectively subtract the laser phase noise in sideband 154L from the laser phase noise in tone 156, resulting in significant cancellation of this noise source. In contrast, using the sum component would effectively reinforce the laser phase noise.

[0054] Processing the sidebands 154 separately from each other is also advantageous because it significantly reduces dispersion effects caused by fiber 120. For example, in direct detection receivers processing a double sideband signal, upper and lower sidebands 154U and 154L would be processed together and, at certain frequencies for the sidebands 154 and lengths of fiber 120, the dispersion effects of fiber 120 would cause the two sidebands to destructively interfere, significantly impairing the recovery of information signal 140. By processing sidebands 154 separately from each other, signal recovery device 190 avoids this deleterious dispersion effect.

[0055] In a preferred embodiment, heterodyne detector 180 includes a combiner 136 and a square law detector 137 coupled in series. Combiner 136 preferably is a fiber coupler, due to its low cost and applicability to fiber systems, although other types of combiners may be used. Square law detector 137 preferably is a PIN diode. Combiner 136 receives the incoming optical signal 142 at one of its inputs and receives the optical local oscillator signal 134 at the other input. Combiner 136 combines the local oscillator signal 134 with the optical signal 142 to produce the combined signal with spectrum 160. The heterodyne detector 180 may also include a polarization controller 139 coupled to the combiner 136 for matching the polarizations of the optical signal 142 and the local oscillator signal 134 so that the two signals are mixed efficiently at the square law detector 137.

[0056] In a preferred embodiment, as illustrated in more detail in FIG. 1B, single sideband modulation may be further achieved by using a filter (not shown) to substantially attenuate one sideband 144 with respect to the other. In the example of FIG. 1B, the lower sideband 144L is attenuated with respect to the upper sideband 144U. Furthermore, the tone may be located at a frequency  $f_t$  which is separate from the carrier frequency. The carrier is suppressed. The transmitted optical signal 142 then includes a tone 146 separate from the optical carrier, a single sideband 144U and a suppressed optical carrier 147. At square law detector 137, the relevant components of optical signal 160 include a tone, single sideband and optical local oscillator.

[0057] In one embodiment of the system shown in FIG. 1B, the modulator 114 includes a conventional two-arm Mach-Zender modulator (MZM) that is biased at a minimum point of its raised cosine transfer function. Operation at the minimum point suppresses the optical carrier and the result is an optical data signal that includes two sidebands and no (or a reduced) optical carrier. The information signal driving the MZM includes a pilot tone as well as data (e.g., possibly encoded onto multiple subcarriers). Each sideband of the MZM output then includes an image of both the pilot tone and data. An optical filter attenuates one sideband with respect to the other. The remaining sideband then includes the data carrying sideband 144U as well as a pilot tone 146. The system in FIG. 1B otherwise operates similarly to that of FIG. 1A.

[0058] FIG. 12 is a block diagram of a corresponding signal recovery device 190. Signal recovery device 1790 preferably comprises an information signal splitter 1705 coupled to a local oscillator generator 1750 and to a demodulator 1760. Local oscillator generator 1750 is also coupled to demodulator 1760.

[0059] In one embodiment, information signal splitter 1705 includes an electrical signal splitter 1710, a pilot tone recovery arm 1720 and a data recovery arm 1740. Electrical signal splitter 1710 is configured to receive electrical signal 150 from heterodyne detector 180 (see FIG. 1B) and is coupled to each recovery arm 1720 and 1740. The pilot tone recovery arm 1720 recovers the pilot tone 1725 (same as 156). It is also coupled to local oscillator generator 1750, which receives pilot tone 1725 and generates an electrical local oscillator 1755 at the frequency  $f_{osc}$ , which is identical to frequency  $f_s$  of data signal 1745. Electrical local oscillator 1755 is generated by mixing pilot tone 1725 with reference frequency  $f_r$ . The data recovery arm 1740 recovers the data signal 1745, located at frequency  $f_s$ . Both the data recovery arm 1740 and local oscillator generator 1750 output to demodulator 1760, which outputs recovered data stream 170.

[0060] In signal 150, pilot tone 156 and the data carrying channel 154U carry correlated phase noise, including laser phase noise, since they were generated and transmitted together in transmitter 110 and detected together in heterodyne receiver 130. Signal paths for pilot tone recovery arm 1720 and data recovery arm 1740 are matched so that the phase noise experiences the same group delay in these two arms. Thus, data signal 1745 and local oscillator 1755 are correlated at demodulator 1760 and the phase noise cancels at demodulator 1760.

[0061] Returning to FIG. 1A, in a preferred embodiment, the polarization controller 139 matches the polarization of the local oscillator 134 to the polarization of the tone 146. This matching is particularly advantageous when a polarization tracking algorithm is used because the tone 146 is stable and does not have substantial amplitude variation and therefore provides better locking of the polarizations. In fibers having measurable polarization mode dispersion, after propagation through the fiber, each sideband 144 and the tone 146 can have slightly different polarizations, thus resulting in attenuation of the detected electrical signal due to the polarization mismatch. Generally, the further the

separation in frequency between the sideband 144 and the tone 146, the stronger the attenuation of the detected electrical signal. This attenuation can be mitigated by boosting the transmit power of the affected subbands.

[0062] In FIG. 1A, the polarization controller 139 is shown located between the local oscillator 132 and combiner 136 and controls the polarization of the local oscillator signal 134. Alternately, the polarization controller 139 may be located between the fiber 120 and combiner 136 and control the polarization of the optical signal 142. In another approach, polarization controller 139 may control the polarizations of both signals 134 and 142. Square law detector 137 produces a photocurrent which is proportional to the intensity of signal 160, which effectively mixes together the various frequency components in spectrum 160. The resulting electrical signal has a number of frequency components located at different frequencies, with the components of interest shown by spectrum 150. Spectrum 150 is similar to spectrum 142, but frequency downshifted from the carrier frequency  $f_c$  to the difference frequency  $\Delta f$ .

[0063] The signal recovery device 190 processes the spectrum 150 to recover the original information signal 140. FIGS. 2 and 3 are block diagrams of example signal recovery devices 190.

[0064] FIG. 2 is a block diagram of one embodiment 290 of signal recovery device 190 based on squaring a signal containing a tone and a sideband. Signal recovery device 290 includes a bandpass filter 210, a square law device 220, and a low pass filter 230 coupled in series. The filters 210, 230 may be implemented in many different ways, for example, by a DSP chip or other logic device implementing a digital filter, a lump LC filter, a surface acoustic wave filter, a crystal-based filter, a cavity filter, or a dielectric filter. Other implementations will be apparent. The square law device 220 also may be implemented in many different ways. A diode is one common implementation.

[0065] Signal recovery device 290 recovers the information signal 140 from electrical signal 150 as follows. Bandpass filter 210 frequency filters one of the sidebands and one of the tones from electrical signal 150. In this example, signal 150 includes two sidebands 154 and an optical carrier 156. Bandpass filter 210 passes the upper sideband 154U and the

optical carrier 156, and blocks the lower sideband 154L, thus producing spectrum 260. The square law device 220 squares the filtered components 260, resulting in spectrum 270. Spectrum 270 includes frequency components 272 located at the difference of frequencies between sideband 154U and tone 156, and also frequency components 274 located at the sum of these frequencies. Low pass filter 230 selects the difference components 272, thus recovering the information signal 140.

[0066] As noted previously, selection of the difference components 272 rather than the sum components 274 is advantageous because it effectively cancels any noise sources which are common to both the tone 156 and sideband 154. In addition, processing a single sideband 154U, rather than both sidebands 154U and 154L together, prevents any potential destructive interference between the sidebands, as may be caused by the frequency dispersion effects discussed previously.

[0067] FIG. 3 is a block diagram of another embodiment 390 of signal recovery device 190 based on multiplying a tone with a sideband. This device 390 includes two bandpass filters 310 and 312, a multiplier 320 and a low pass filter 330. The two bandpass filters 310, 312 are each coupled to receive the incoming electrical signal 150 and are coupled on their outputs to multiplier 320. The multiplier is coupled to low pass filter 330. If transmitted signal 150 is a single sideband signal (i.e., either sideband 154L or 154U is substantially attenuated), the filter 312 may be optional.

[0068] Bandpass filter 310 selects a tone 156 and bandpass filter 312 selects one of the sidebands 154. In this specific example, the optical carrier and upper sideband 154U are the selected components. Multiplier 320 multiplies the tone 156 against the selected sideband 154U, resulting in a signal with a sum component 374 and a difference component 372, as in FIG. 2. Low pass filter 330 selects the difference component 372, thus recovering the information signal 140. Upper and lower electrical signal paths are matched to cancel phase noise, including laser phase noise.

[0069] In the above examples, the optical carrier played the function of the tone 146. FIG. 4 illustrates an example in which a tone 146 is located at a frequency other than the carrier frequency. In particular, FIG. 4 is a diagram of one embodiment 410 of transmitter

100 using a pilot tone. Transmitter 410 includes an optical source 112 coupled to an MZM 114. However, transmitter 410 also includes an electrical combiner 420 and a pilot tone generator 430. The pilot tone generator 430 is coupled to one input of combiner 420, the output of which drives MZM 114. The other input of combiner 420 receives information signal 140.

[0070] In transmitter 410, combiner 420 combines the pilot tone at a frequency  $f_p$  with the incoming information signal 140 and uses the combined signal to modulate MZM 114. If MZM 114 is biased at one of the extremum points of the raised cosine transfer function, the resulting spectrum 440 will include upper and lower sidebands 444 of the information signal, upper and lower sidebands 448 of the pilot tone, and no optical carrier. Each sideband 448 of the pilot tone may be used by signal recovery device 190 as a tone 146. In other words, the signal recovery device may mix one of the pilot tones 448 with one of the sidebands 444 to recover the information signal 140.

[0071] All of the signal recovery devices 190 described above may be adapted for use with optical data signal 440. For example, referring to FIG. 2, bandpass filter 210 may be adjusted to select one of the sidebands 444 and one of the pilot tones 448. The square law device 220 would then produce a corresponding difference component 272. Since this difference component might not lie exactly at baseband, low pass filter 230 may also need to be adjusted in order to recover the correct frequency components. Similarly, referring to FIG. 3, device 390 may be adapted for use with signal 440 by similarly adjusting the frequency bands for filters 310, 312, and 330 to select an appropriate sideband 444, pilot tone 448 and difference component 372, respectively. Transmitter 410 and optical data signal 440 are merely illustrative, other combinations of tones and sidebands will be apparent.

[0072] FIGS. 1-4 illustrate various embodiments of transmitter 110 and receiver 130. These embodiments are illustrated primarily using the example in which optical data signal 142 includes two optical sidebands 144 and the optical carrier functions as a tone 146. The invention, however, is not limited to any of these specific examples. Transmitter and receiver designs other than those shown may be used. Modulation schemes besides double sideband may be used. In a preferred embodiment, the modulation is single sideband.

Similarly, the tone 146 may be located at frequencies other than the carrier frequency  $f_c$  and/or multiple tones 146 may be used. For further examples of transmitters, receivers, and modulation approaches, see also the following co-pending U.S. Patent Applications: Serial No. 09/918,886, "Optical Communications Using Multiplexed Single Sideband Transmission And Heterodyne Detection," by Ting K. Yee, et al., filed July 30, 2001; Serial No. 09/747,261, "Fiber Optic Communications using Optical Single Sideband Transmission and Direct Detection," by Ting K. Yee and Peter H. Chang, filed Dec. 20, 2000; Serial No. 09/728,373, "Optical Communications Using Heterodyne Detection," by Ting K. Yee and Peter H. Chang, filed Nov. 28, 2000; and Serial No. 09/474,659, "Optical Communications Using Heterodyne Detection," by Ting K. Yee and Peter H. Chang, filed Dec. 29, 1999. All of the foregoing are incorporated herein by reference.

**[0073]** FIG. 5 is a block diagram of a bidirectional fiber optic communications system 500. System 500 includes two transceivers 501E and 501W which communicate with each other over two optical fibers 120E and 120W. The letters "E" and "W" stand for east and west, denoting two different directions for data flow. Each transceiver 501 includes an optical data input and an optical data output. The optical data output of one transceiver 501 is coupled to the optical data input of the other transceiver via an optical fiber 120. Each transceiver 501E and 501W also includes a transmitter-receiver pair 505E and 505W, respectively. A distinction is made between transceivers 501 and transmitter-receiver pairs 505 because, as will be illustrated below, a transceiver can include more than one transmitter-receiver pair.

**[0074]** Each transmitter-receiver pair 505 includes a transmitter and a receiver. The transmitters and receivers described previously are suitable for use in the transmitter-receiver pairs 505. For purposes of illustrating aspects of the invention, the majority of the transmitter and receiver are represented by blocks 510 and 530, respectively. More specifically, the transmitter 510 is a transmitter as described above (e.g., transmitter 110 in FIG. 1), but not including the optical source 112. Similarly, the receiver 530 is a heterodyne receiver as described above (e.g., receiver 130 in FIG. 1), but not including the optical LO source 132. These two sources are shown separately in FIG. 5 and, in fact, are implemented as a single laser source 520. The laser source 520 is coupled to an optical splitter 527, which in turn is coupled to the optical transmitter 510 and heterodyne receiver 530.

[0075] Each transmitter-receiver pair 505 operates as follows. The laser source 520 generates a laser beam 525, which is split by the optical splitter 527 into two beams, which shall be referred to as a source beam 515 and a local oscillator beam 535. The source beam 515 is received by the “sourceless” transmitter 510 and functions as the optical carrier for the transmitter 510. The LO beam 535 is received by the “sourceless” heterodyne receiver 530 and functions as the LO for the receiver 530. The various beams may be transmitted via free space and/or by guided structures, such as fibers or waveguides. The term “beam” is not intended to imply that the optical signal is a free space beam.

[0076] The system 500 operates as follows. In the eastbound direction, transmitter 510W receives an electrical data signal, modulates the source beam 515W from laser source 520W with the electrical data signal, and transmits the resulting optical data signal via fiber 120E to heterodyne receiver 530E. The heterodyne receiver 530E recovers the electrical data signal from the received optical data signal. It uses the LO beam 535E from laser source 520E as an optical local oscillator in this process. In the westbound direction, transmitter 510E transmits data to receiver 530W via fiber 120W in an analogous fashion.

[0077] In order for the heterodyne detection to function properly, the two laser beams 525E and 525W cannot have arbitrary wavelengths with respect to each other. Let laser beam 525E have a wavelength of  $\lambda_E$  and laser beam 525W have a wavelength of  $\lambda_W$ . In the eastbound direction, the optical carrier for transmitter 510W is based on the laser beam 525W and therefore has a wavelength of  $\lambda_W$ . At receiver 530E, the corresponding LO is based on the laser beam 525E and therefore has a wavelength of  $\lambda_E$ . In the westbound direction, the optical carrier has a wavelength of  $\lambda_E$  and the LO has a wavelength of  $\lambda_W$ . As is discussed above, the LO and optical carrier generally are separated in frequency by a known amount, denoted by  $\Delta f$ , and must maintain this frequency separation in order for the heterodyne detection to work properly. In a preferred embodiment, the wavelengths of the two laser beams 525E and 525W are maintained at the frequency separation of  $\Delta f = 0$ . In an alternate embodiment,  $\Delta f \neq 0$  so that there is a frequency offset between the two laser beams 525E and 525W. Thus, in one direction, the LO will be higher in frequency than the optical carrier by  $\Delta f$  and, in the other direction, the LO will be lower in frequency than the optical carrier by  $\Delta f$ .

[0078] The frequency separation can be maintained in a number of ways. In one approach, each laser source 520 is locked to a known wavelength. For example, each laser source 520 can be independently locked to the same wavelength if  $\Delta f = 0$  or to offset wavelengths if  $\Delta f \neq 0$ . The exact numbers can be factory set or provisioned in the field. One advantage of this approach is that the two transmitter-receiver pairs 505 need not communicate with each other before bringing up their respective laser sources 520. Rather, transmitter-receiver pair 505E simply brings up its laser source 520E and locks it to the reference frequency. Transmitter-receiver pair 505W does the same. Each laser source 520 locks the wavelength of its laser beam 525 without using the laser beam from the other laser source. The locking, however, must be accurate in absolute terms since there is no feedback to ensure that the laser sources 520 maintain the constant frequency separation over time. For example, if laser source 520E begins to drift, there is no feedback loop to ensure that laser source 520W maintains the required frequency separation from laser source 520E.

[0079] In an alternate approach, each laser source 520 is actively locked to the other. For example, if  $\Delta f \neq 0$ , laser source 520E might be locked to  $\Delta f$  above the frequency of the optical carrier received from transmitter 510W. Similarly, laser source 520W would be locked to  $\Delta f$  below the frequency of the optical carrier received from transmitter 510E. One advantage of this approach is that the lock is maintained even if one link is lost. For example, if fiber 120E is cut, data can still be transmitted in the westbound direction over fiber 120W since the laser source 520W is actively locked to the optical carrier from transmitter 510E. However, care must be taken to avoid inconsistent locking when  $\Delta f \neq 0$  (e.g., if each laser source attempts to lock to  $\Delta f$  above the other laser source) and also to avoid unwanted conditions, such as race conditions or maintaining the correct frequency separation but centered around a wrong center frequency.

[0080] In another approach, one transceiver is a master transceiver and the other is a slave transceiver. For example, assume that the west transceiver 501W is master and the east transceiver 501E is slave. The laser source 520W in the master transceiver 501W locks to a frequency without using the laser beam 515E from the slave transceiver 501E. The laser source 520E in the slave transceiver 501E locks to the optical signal received from the master transceiver 501W. For example, laser source 520W might be locked to a frequency of 193.1 THz (one of the wavelengths on the ITU grid), and laser source 520E locked to the

same wavelength as the optical carrier of the master transceiver 501W. Laser source 520E may do this by locking to the actual optical carrier if it is transmitted. Alternately, if the optical signal from master transceiver 501W contains a component which is offset by a known amount  $\delta f$  relative to the optical carrier, the laser source 520E may be locked to this component, but offset by the amount  $\delta f$  thus in effect locking to the carrier frequency. Furthermore, laser source 520E may be locked to the component but offset by an amount other than  $\delta f$ , for example if the two laser sources 520E and 520W are locked to different wavelengths. Advantages of this approach are that the frequency separation is actively maintained as is the lock to a reference frequency.

[0081] FIGS. 6 and 7 illustrate two types of wavelength locking devices. In FIG. 6, a laser source 520 is locked to a fixed reference frequency, as is the case in a master transceiver. In FIG. 7, a laser source 520 is locked relative to a separate optical beam, as is the case in a slave transceiver. Wavelength-locking devices other than those shown in FIGS. 6 and 7 may also be used. For example, see co-pending U.S. Patent Application Serial No. 09/746,370, "Wavelength-Locking of Optical Sources," by Shin-Sheng et al., filed Dec. 20, 2000, which is incorporated by reference herein.

[0082] FIG. 6A is a block diagram of wavelength locking device 600. Device 600 includes an etalon 620, two detectors 630 and 640, and control circuitry 650. The etalon 620 is coupled to receive the laser beam 525 from the laser source 520. Typically, a small portion of the laser beam 525 from laser source 520 is tapped and fed to wavelength locking device 600. The two detectors 630 and 640 are coupled to measure the strength of the laser beam entering and exiting the etalon 620, respectively. The control circuitry 650 is coupled to receive the outputs of the two detectors 630 and 640. It optionally also receives a temperature measurement of the etalon 620. The control circuitry 650 is coupled to provide feedback to the laser source 520 in order to lock its wavelength to a fixed reference.

[0083] FIG. 6B is a spectral diagram illustrating operation of the wavelength locking device 600. Device 600 locks the laser source 520 to a fixed reference wavelength of 193.1 THz - 41 GHz in the following example. The frequency 193.1 THz is one of the wavelengths specified in the ITU grid, as defined in ITU-T Recommendation G.692 "Optical Interfaces for Multichannel Systems with Optical Amplifiers." The nature of the

41 GHz offset will be described more fully with respect to FIG. 11 below. Curve 650 shows the intensity of the laser beam received by the pre-etalon detector 630 as a function of frequency. Since there are no frequency-dependent devices in the path between the laser source 520 and the pre-etalon detector 630, curve 650 is flat. Curve 660 shows the intensity of the laser beam received by the post-etalon detector 640 as a function of frequency. The etalon 620 has a periodic spectral response. In this example, the period is chosen to match the ITU grid so that a single etalon 620 can be used across the entire grid.

[0084] The etalon's spectral response is selected and attenuation is introduced in the pre-etalon path so that the two curves 650 and 660 intersect at the desired frequency 670. For the curves shown, one of these intersections 670 occurs at a frequency of 193.1 THz - 41 GHz. Thus, if the laser beam 525 has a frequency of 193.1 THz - 41 GHz, the signals produced by the detectors 630 and 640 will be equal in strength. Alternatively, attenuation may be introduced in the pre-etalon path so that, if the laser beam 525 is at the correct frequency, the signals produced by detector 630 and 640 will have a predetermined ratio. At frequencies above the target frequency, the post-etalon detector 640 produces a weaker signal than the pre-etalon detector 630. At frequencies below the target frequency, the post-etalon detector 640 produces a stronger signal. The control circuitry 650 generates a feedback signal based on comparing the signals from the two detectors 630 and 640 to drive the laser beam 525 to the reference frequency. Control circuitry 650 can include attenuation or gain setting to select a bias condition. Generally, the response of etalon 620 varies slightly with temperature. Therefore, temperature measurements from etalon 620 can be used to further refine the accuracy of the feedback signals produced by control circuitry 650.

[0085] FIG. 7 is a block diagram of a wavelength-locking device 700 in which the laser source 520 is locked relative to an incoming optical beam, which shall be referred to as an optical reference signal 752. For example, in the context of FIG. 5, the optical reference signal 752 may be a certain frequency component received from the master transceiver 501W (e.g., the optical carrier or a pilot tone contained in the waveform), and the wavelength-locking device 700 locks the slave laser beam 525E to a certain frequency offset with respect to the frequency component. For example, if the optical carrier of 193.1 THz - 41 GHz from master transceiver 501W is used as the optical reference signal 752, the slave laser source 520E can be locked to the same wavelength as the optical reference signal. On

the other hand, if a 30 GHz pilot tone is used as the optical reference signal 752, the reference signal will be located at 193.1 THz - 11 GHz. Therefore, the slave laser source 520E can be locked to 30 GHz below this optical reference 752 to meet the target frequency of 193.1 THz - 41 GHz. The example of FIG. 7 illustrates this latter case in which the optical reference signal 752 includes a suppressed optical carrier 147, a tone 146 located 30 GHz above the carrier, and a single sideband 144U, as would be produced by the system of FIG. 1B. The tone 146 is used as the reference.

[0086] Device 700 includes a square law detector 712 coupled to a conventional phase-locked loop 720 via a band pass filter 714. The phase-locked loop 720 is also coupled to receive a signal from a reference oscillator 730. Device 700 operates as follows. The optical reference signal 752 is combined with the laser beam 525 (e.g., by an optical combiner), shown at a frequency  $f_{LO}$ , and the combined signal is received by the square law detector 712. This effectively mixes the two signals together, generating a component at a beat frequency  $f_b$  between the two signals. The bandpass filter 714 isolates the beat component, in this example filtering out the sideband carrying data. The beat component is received by the phase-locked loop 720, which also receives a 30 GHz reference sinusoid from oscillator 730. The phase-locked loop 720 provides feedback to the laser source 520, adjusting its output wavelength, in order to lock the beat component with the reference sinusoid.

[0087] Returning now to FIG. 5, one approach to maintaining a frequency separation between the two laser sources 520 was based on designating one transceiver 501W as master and the other 501E as slave. The master/slave determination itself can be accomplished in many different ways. In the approach shown in FIG. 8A, each transceiver 501 is set 810 for one of three modes: master, slave or negotiation. In the master mode, the transceiver 501 acts as a master and its laser source 520 locks 820 without using the other transceiver's laser beam. For example, the laser source 520 may use the wavelength-locking device of FIG. 6 to lock to a reference frequency. In the slave mode, the transceiver 501 acts as a slave and its laser source 520 locks 830 relative to the laser beam from the other transceiver. For example, the laser source 520 may use the wavelength-locking device of FIG. 7 to lock to some frequency component of the optical data signal received from the

other transceiver. In the negotiation mode, the transceiver “negotiates” 840 whether it is master or slave.

[0088] FIG. 8B is a flow diagram illustrating one example of negotiating 840 master/slave roles. Each transceiver 510 has a sequence of bits which represents potential roles of master and slave. The bit sequences can be randomly generated or can be based on some quasi-random or unique sequence. In a preferred embodiment, a pseudo-random sequence of 1’s and 0’s is generated, representing master and slave, respectively. For example, the sequence 01011011110 . . . might be generated for transceiver 501W and 01100101110 . . . for transceiver 501E. Alternately, the BCD equivalent of the transceiver 501’s serial number can be used to generate the sequence of 1’s and 0’s.

[0089] In step 841, the transceivers 501 determine whether they can communicate with each other. If they can, each transceiver 501 transmits 844 whether it is master or slave according to its bit sequence and also receives 844 the other transceiver’s state. If the states are consistent 846 (i.e., one transceiver is master and the other is slave), the negotiation ends 848. Otherwise, it continues and each transceiver 501 selects 842 to be either master or slave, according to the next bit in its bit sequence (going left to right in this example). For the example sequences given, both transceivers first attempt to be slave (0 bit) during the first exchange and master (1 bit) for the second exchange. In the third time exchange, the negotiation is resolved with transceiver 501E being master (1 bit) and 501W being slave (0 bit).

[0090] If, in step 841, the transceivers 501 cannot communicate with each other (or if they lose the communications link at some point), then each transceiver 501 cycles through its bit sequence over time. In more detail, time is divided into discrete time periods. Each transceiver waits 852 the time period and then selects 854 to be either master or slave according to its bit sequence. When the transceivers cycle to a master/slave situation, they should be able to establish communications and proceed to the “yes” branch from step 841.

[0091] In one embodiment, whether a transceiver is a master or a slave is transmitted to the other transceiver over fibers 102 but using a communications channel which is more robust than the communications channels normally used for data communication between

the transceivers, especially since a much lower data rate typically is sufficient for the master/slave negotiation. Both transceivers could use the communications channel to exchange unique information, for example serial number, MAC address, or a pseudo-random sequence, with this information used to determine master and slave roles. For example, in one implementation, during normal data communications, the laser sources 520 are modulated at high data rates (e.g., tens of Gbps) using sophisticated and spectrally efficient modulation schemes (e.g., QPSK or QAM) and heterodyne recovery. In contrast, during the master/slave negotiation, the laser sources 520 are modulated using low frequency AM modulation of a subcarrier at much lower data rates (e.g., tens of bps) and direct detection. This is advantageous because the master/slave negotiation likely occurs as part of the process for establishing the normal communications channels between the two transceivers 501, in which case the normal communications channel probably is not available yet.

[0092] Other approaches for determining the master and slave roles will be apparent. In one approach, one transceiver 501W is manually configured to be master and the other 501E to be slave. One advantage to this approach is that when a transceiver is set in either master or slave mode, it can determine its role without communicating with the other transceiver.

[0093] In a different approach, the transceiver which first begins transmission is the master and the other transceiver is the slave. Thus, if a transceiver is transmitting but has not yet received transmissions, it assumes the role of master. Similarly, if the transceiver receives transmissions before it itself transmits, it assumes the role of slave.

[0094] Alternately, master/slave can be determined based on the wavelength of transmission. In one approach, each transceiver is allowed to begin transmission. Each transceiver compares the wavelength of its laser source 520 with the wavelength received from the other transceiver. The laser source 520 with the shorter wavelength is master and the other laser source is slave. Conventional techniques such as waiting a random period of time and then redetermining master/slave can be used to avoid inconsistent decisions (e.g., if both transceivers decide they are master). One advantage of these approaches is that the master/slave determination is made based solely on information which is local to the

transceiver. No data need be communicated from one transceiver to the other and, therefore, no communications link between the transceivers need be established in order to determine the master/slave roles.

[0095] As a final point, even if a transceiver 501 is set in slave or negotiation mode, it is advantageous to first bring up the transceiver in master mode and then switch to slave or negotiation mode. This is because in master mode, the transceiver 501 is able to set its laser source 520 to a wavelength which is in the general vicinity of the final target wavelength, thus preventing gross errors. Furthermore, the transceiver 501 can do this without communicating with the other transceiver or receiving an optical data signal from the other transceiver.

[0096] In many cases, the assignment of master and slave roles may depend on the order in which the transceivers are brought up. In addition, if the wavelengths are sufficiently close and stable, a master/master or slave/slave assignment may be usable.

[0097] FIG. 9 is a block diagram of another bidirectional fiber optic communications system. System 900 is similar to system 500 of FIG. 5, except that each transceiver 901 has two transmitter-receiver pairs 505(A) and 505(B), which communicate with each other over the four optical fibers 120E(A), 120E(B), 120W(A) and 120W(B). In more detail, there are two sets (A) and (B) of corresponding transmitter-receiver pairs. Transmitter-receiver pairs 505W(A) and 505E(A) coupled by fibers 120W(A) and 102E(A) form one set, and 505W(B) and 505E(B) coupled by fibers 120W(B) and 102E(B) form the other set. Each set functions the same as system 500 in FIG. 5. In the eastbound direction, transmitters 510W(A) and 510W(B) send data to heterodyne receivers 530E(A) and 530E(B) via optical fibers 120E(A) and 120E(B), respectively. In the westbound direction, transmitters 510E(A) and 510E(B) send data to heterodyne receivers 530W(A) and 530W(B) via optical fibers 120W(A) and 120W(B), respectively. Each transmitter-receiver pair 505 includes a single laser source 520, which supplies both a source beam 515 to transmitter 510 and a LO 530 to the heterodyne receiver 530, as described previously. In alternate embodiments, the transceiver can contain more transmitter-receiver pairs.

[0098] FIG. 10 is a block diagram of another bidirectional fiber optic communications system. This system 1000 contains two transceivers 1001E and 1001W, each with two transmitter-receiver pairs 505, as in FIG. 9. However, there are only two optical fibers 102E and 102W, which are shared by the transmitter-receiver pairs. In the eastbound direction, transmitter 510W(A) sends data to heterodyne receiver 530E(A) via optical fiber 120E, and transmitter 510W(B) sends data to heterodyne receiver 530E(B) via the same optical fiber 120E. In the example shown, the two transmitters 510W operate at different wavelengths and are combined using wavelength division multiplexing (WDM).

[0099] The transceiver 1001W includes an optical combiner 1003W which combines the two data signals from the transmitters 510W. Examples of optical combiner 1003W include WDM multiplexers and power combiners. On the receive side, transceiver 1001E includes an optical splitter 1007E which separates the signals and send them to the appropriate heterodyne receiver 530W(A) or 530W(B), respectively. Examples of optical splitter 1007E include WDM demultiplexers and optical power splitters. Filters may be located at various points along the signal paths in order to improve performance by attenuating unwanted signals and/or reducing noise. For example, optical filters can be placed between transmitters 510W and combiner 1003, after combiner 1003, before splitter 1007 and/or between splitter 1007 and heterodyne receivers 530E. The westbound direction operates analogously, using optical combiner 1003E in transceiver 1001E and optical splitter 1007W in transceiver 1001W.

[0100] In one implementation, the transceiver(s) 1001 further include a wavelength-locking device, such as those described previously, to lock the laser sources 520 within the transceiver to each other. For example, the laser sources 520E(A) and 520E(B) can be locked to different fixed offsets consistent with the ITU grid. For example, laser source 520E(A) might be locked to a certain frequency offset below one of the wavelengths on the ITU grid and laser source 520E(B) locked to a certain frequency offset above the same ITU wavelength. If the frequency offsets are small enough, the resulting combined signal will fall within the frequency band allocated to the ITU wavelength and the combined signal can be tested as a single signal in a DWDM optical networking system.

[0101] FIG. 11 is a block diagram of yet another bidirectional fiber optic communications system 1100 capable of transporting 40 Gbps in each direction. System 1100 is similar to system 1000 in that each transceiver 1101E and 1101W includes two transmitter-receiver pairs 505. FIG. 11 shows only the eastbound direction of the overall system. The westbound direction is similarly constructed. The elements for the westbound direction and the shared laser sources 520 are omitted for clarity.

[0102] System 1100 operates as follows. Each optical transmitter 510W(A) and 510W(B) produces an optical data signal 1660A and 1660B, respectively, which eventually is transmitted down the fiber as a combined, optical single sideband signal. Each optical data signal 1660 includes one or more subband(s) and tone(s) for eventual heterodyne detection. In this particular example, optical signal 1660A is a double-sideband signal having an upper optical sideband 1668A(U), a lower optical sideband 1668A(L), and a suppressed carrier 1669A. In an alternate embodiment, the carrier 1669A may not be suppressed in the optical transmitter 510W, but suppressed later, for example by optical filter 1615. Upper sideband 1668A(U) includes subbands 1662A(U), 1663A(U), 1665A(U) and 1666A(U), and tone 1664A(U). Lower sideband 1668A(L) includes the mirror image: subbands 1662A(L), 1663A(L), 1665A(L) and 1666A(L), and tone 1664A(L).

[0103] Note that in this example, the subbands 1662A, 1663A, 1665A and 1666A are not upper and lower sidebands resulting from an electrical double sideband modulation in which signal 1664A is an electrical carrier. Rather, each subband 1662A, 1663A, 1665A and 1666A carries different information and may itself contain sub-subbands. Signal 1664A is a tone.

[0104] In one implementation, the transmitter 510 receives a number of data tributaries which are conditioned and then combined using conventional frequency division multiplexing (FDM) techniques. In more detail, the tributaries are received by electrical stages which condition the tributaries. Different tributaries will undergo different types of conditioning. Thus, the electrical stages need not be identical. Error correction encoding, interleaving, electrical modulation (e.g., QAM or QPSK modulation), serializing/deserializing, splitting or combining tributaries to generate outputs of lower or higher data rates, and shifting information to different central frequencies are examples of

functions which may occur in the electrical stages. The conditioned signals are combined by a FDM multiplexer to generate the electrical data signal fed to the optical modulator 114. The receiver 530 contains an analogous structure to reverse the operations performed at the transmitter 510. For further examples, see also the following co-pending U.S. Patent Applications: Serial No. 09/918,886, "Optical Communications Using Multiplexed Single Sideband Transmission And Heterodyne Detection," by Ting K. Yee, et al., filed July 30, 2001; and Serial No. 09/405,367, "Optical Communications Networks Utilizing Frequency Division Multiplexing," by Michael W. Rowan, et al., filed Sept. 24, 1999. All of the foregoing are incorporated herein by reference.

[0105] Returning to FIG. 11, optical data signal 1660B is structured similarly to optical data signal 1660A, containing two optical sidebands 1668B and a suppressed carrier 1669B. Each optical sideband 1668B includes four subbands 1662B, 1663B, 1665B and 1666B, and a tone 1664B. The subbands 1662B, 1663B, 1665B and 1666B are different from the subbands 1662A, 1663A, 1665A and 1666A; so in this example, there are a total of eight subbands carrying different information. Optical signals 1660A and 1660B are also different in that they are orthogonally polarized. In one embodiment, they are transmitted having orthogonal linear polarizations. In FIG. 11, the orthogonal polarizations are indicated by the orientation of the spectra. For example, spectra 1660A is oriented in the plane of the paper, indicating one polarization; while spectra 1660B is oriented coming out of the paper, indicating an orthogonal polarization. In addition, the two optical signals 1660 use optical carriers 1669 of different wavelengths. In an alternate embodiment, the optical signals 1660 are orthogonally polarized but not using crossed linear polarizations. For example, one signal 1660A may be right circularly polarized; whereas the other signal 1660B would be left circularly polarized. In another embodiment, the two optical data signals have different polarizations but may not be completely orthogonally polarized to each other.

[0106] The two optical signals 1660 are combined in the transceiver 1101W using combiner 1614. The combiner 1614 preferably is a polarized beam combiner, so that optical signals 1660 are minimally attenuated. In this example, the optical carriers 1669 are selected so that in the combined signal 1680, the upper optical sideband 1668A(U) of one signal is adjacent to the lower sideband 1668B(L) of the other signal. Preferably, the

pairing is made so that each sideband 1668A(U) and 1668B(L) lies evenly to either side of a predetermined frequency, for example one of the frequencies specified by the ITU grid.

[0107] Transceiver 1101W also includes an optical filter 1615, which filters out the redundant sidebands: lower sideband 1668A(L) and upper sideband 1668B(U) in this case. Filter 1615 may also substantially attenuate the carriers 1669, particularly if, for example, the optical transmitters 510W do not significantly suppress the carriers 1669. In this example, the optical filter 1615 is shown on the transmit side of the system, located after the optical combiner 1614. However, filtering typically can be implemented at a number of different locations and/or distributed between different locations. For example, an optical filter may also be placed on the receiver side, between fiber 120E and optical splitter 1633. One advantage of this placement is that this optical filter can also filter out noise generated during transmission, such as amplified spontaneous emission (ASE). This is particularly important in single sideband systems when ASE noise may occur at the single sideband image. This ASE is sometimes referred to as the ASE noise image. For example, if the data-carrying sideband occurs at a frequency offset of  $+\Delta f$  relative to the optical local oscillator signal, the ASE noise image would occur at a frequency offset of  $-\Delta f$  relative to the optical local oscillator signal.

[0108] There are other applications for filters. In WDM applications, filters can also be used to suppress unwanted channels. As a final example, optical filters can be placed between the optical transmitters 510W and optical combiner 1614 to filter out the unwanted sidebands and/or suppress the optical carriers.

[0109] In one embodiment, optical filter 1615 is a simple optical bandpass filter. In another embodiment, the optical filter 1615 is implemented as a comb filter, or a series of comb filters. Comb filters have periodic alternating pass and stop bands which repeat on a regular basis. For example, a comb filter might have alternating pass and stop bands, with the spectral response repeating with a periodicity which matches the ITU grid. Thus, a single filter can be used across the entire grid. In one embodiment, the comb filter is implemented as an interleaver, which can also be used to combine sets of wavelengths in WDM applications.

[0110] The resulting composite optical data signal 1690 includes the upper sideband 1668A(U) from optical signal 1660A and the orthogonally polarized lower sideband 1668B(L) from optical signal 1660B. Each of the eight subbands of composite optical data signal 1690 carries different information, for example a different 5 Gbps data stream in one embodiment. Note that composite optical signal 1690 is a single sideband signal in that only one optical sideband of each subband is transmitted. The other optical sideband was removed by filter 1615. System 1600 is merely one example of an approach capable of generating optical single sideband signals.

[0111] In one embodiment, optical signal 1660A is generated using an MZM having a bandwidth of 40 GHz. Subbands 1662A, 1663A, 1665A, 1666A, and pilot tone 1664A are generated using a 20-40 GHz baseband electrical signal, resulting in a 20 GHz gap between optical carrier 1669A and the modulated signal 1668A. Limiting the baseband electrical signal to this range advantageously limits the impact of higher order harmonics. Second order harmonics fall outside this range. Limiting the baseband electrical signal to this range also limits the impact of relative intensity noise of the laser source. Relative intensity noise typically occurs in the range of about 0 to 12 GHz. Using QPSK to modulate subcarriers, a data rate of 20 Gbps can be achieved using a bandwidth of about 20 GHz. The total bandwidth includes the bandwidth of each subcarrier, the bandwidth of the pilot tone, and the guard bands between associated with the subcarriers and pilot tone. Optical signal 1660B is similarly generated, having a 20 GHz data bandwidth and a 20 GHz gap between optical carrier 1669B and the modulated signal.

[0112] Thus, a composite signal 1690 having a data rate of 40 Gbps and bandwidth of about 40 GHz comprises two signals 1668A(U), 1668B(L) having a bandwidth of about 20 GHz each, each generated using a modulator having a usable bandwidth of 40 GHz operating in the range of 20 to 40 GHz. More generally, a composite signal having a bandwidth of about X GHz comprises two signals having a bandwidth of about X/2 GHz each. Each such signal is generated using a modulator having a usable bandwidth of X GHz operating in the range of X/2 GHz to X GHz. In a preferred embodiment, the two signals are separated by a guard band that has a width of approximately 10% X. For QPSK modulation, the data rate may be about X Gbps.

[0113] The total bandwidth of optical signal 1690 can be reduced by the selection of frequencies for the optical carriers 1669A, 1669B for the optical signals 1660A and 1660B, respectively. Assume for the moment that transceiver 1001W is a master transceiver and transceiver 1001E is a slave. Referring to FIGS. 6A and 6B, for master transceiver 1001W in which both optical transmitters 510W operate in master mode, optical carrier 1669A is locked to point 670 at a frequency of  $193.1 \text{ THz} - 41 \text{ GHz}$ , and optical carrier 1669B is locked to point 671 at a frequency of  $193.1 \text{ THz} + 41 \text{ GHz}$ , for example using the wavelength locking device 600 shown in FIG. 6A. This wavelength locking approach ensures that optical carriers 1669A, 1669B are symmetrically disposed about the center frequency  $193.1 \text{ THz}$  and that the modulated signals 1669A(U), 1669B(L) do not overlap; while at the same time keeping the separation between the modulated signals 1669A(U), 1669B(L) to a narrow guardband of a few GHz, typically 2-4 GHz for this example.

[0114] One feature of the use of etalon 620 in this manner is that the two optical carriers 1669 are locked at a frequency separation that differs significantly from the base frequency period of the etalon (which is 50 GHz in the example of FIG. 6B) and harmonics of the base period. This feature is accomplished by centering a peak frequency 672 of the etalon spectral response at the center wavelength ( $193.1 \text{ THz}$  in this example) and then locking each optical carrier 1669 to frequencies 670, 671 symmetrically disposed to either side of the peak frequency. In alternate embodiments, the optical carriers may be locked to frequencies which are not symmetric about the etalon's peak frequency or which lie to the same side of the peak frequency.

[0115] Another approach to locking the two optical carriers in the master transceiver 1101W is to lock the frequency of optical carrier 1669A to an etalon 620 (or other reference device) and to lock the frequency of optical carrier 1669B relative to optical carrier 1669A (to 82 GHz above the wavelength of optical carrier 1669A in this case). The wavelength locking device 700 of FIG. 7 may be used for this purpose. Referring to both FIGS. 7 and 11, the optical carrier 1669A (which is wavelength locked to an etalon) corresponds to the optical carrier 147 in FIG. 7. The optical carrier 1669B (which is to be locked to 82 GHz above optical carrier 1669A) corresponds to the laser beam 525 in FIG. 7. The frequency difference  $\Delta f$  in FIG. 7 is the difference between the frequencies of the optical carriers 1669A and 1669B. The phase-locked loop drives  $\Delta f$  to 82 GHz, which is defined in part by

the reference frequency  $f_r$ . The pilot tone 146 and subband 144U are not typically present in this application of wavelength locking device 700.

[0116] In the slave transceiver 1001E, the laser sources are locked to the wavelengths of the optical carriers from the corresponding transmitter in the master transceiver 1001W, for example using the wavelength locking device 700.

[0117] On the receive side, the transceiver 1101E includes an optical splitter 1632 coupled to two heterodyne receivers 530E(A) and 530E(B). Each receiver 530E processes one of the two orthogonally polarized signals 1668A(U) and 1668B(L), respectively, using heterodyne techniques, for example as described previously. Subbands 1662A, 1663A, 1665A and 1666A use tone 1664A in the heterodyne detection. Similarly, subbands 1662B, 1663B, 1665B and 1666B use tone 1664B. The splitter 1632 splits the received composite optical signal 1690 into two optical signals 1692A and 1692B, one for each heterodyne receiver 530. As before, the polarization controller within the receivers 530E matches the polarization of the local oscillator to the polarization of the tone. The local oscillators are wavelength locked using the techniques described previously. Each optical signal 1692 includes the relevant four subbands plus tone. Placing the tone between the subbands reduces the frequency separation between tone and subband, thereby minimizing the attenuation of the detected electrical signal due to polarization mode dispersion. In this implementation, the optical splitter 1632 includes an optical splitter 1633 coupled to two optical filters 1635A-B. In an alternate embodiment, an optical filter is placed upstream of the optical splitter 1633 rather than using two filters 1635A-B downstream of the splitter 1633.

[0118] In a preferred embodiment, each polarized signal 1692A and 1692B is detected using separate optical local oscillators, each of whose polarization is substantially the same as the received signals. The frequency of each local oscillator is the same as the optical carrier corresponding to the respective polarized signal in the composite transmitted signal. Therefore, for a detected signal, the detected modulation falls in the 20-40 GHz range of the square-law device 137, i.e. within one octave. The limitation of the range to one octave is advantageous for the following reasons. It significantly reduces noise due to direct detection products. It simplifies optical filtering of the ASE noise image. It also reduces

second order nonlinear noise in the photodetector and preamp that may comprise square-law device 137.

[0119] Although the invention has been described in considerable detail with reference to certain preferred embodiments thereof, other embodiments will be apparent. For example, other types of transmitters, receivers, and modulation approaches are described in the following co-pending U.S. Patent Applications: Serial No. 09/918,886, "Optical Communications Using Multiplexed Single Sideband Transmission And Heterodyne Detection," by Ting K. Yee, et al., filed July 30, 2001; Serial No. 09/747,261, "Fiber Optic Communications using Optical Single Sideband Transmission and Direct Detection," by Ting K. Yee and Peter H. Chang, filed Dec. 20, 2000; Serial No. 09/728,373, "Optical Communications Using Heterodyne Detection," by Ting K. Yee and Peter H. Chang, filed Nov. 28, 2000; and Serial No. 09/474,659, "Optical Communications Using Heterodyne Detection," by Ting K. Yee and Peter H. Chang, filed Dec. 29, 1999. All of the foregoing are incorporated herein by reference. Therefore, the scope of the appended claims should not be limited to the description of the preferred embodiments contained herein.

WHAT IS CLAIMED IS:

1. A method for generating a composite optical signal having a bandwidth of approximately X, the method comprising:
  - receiving a first electrical signal with a bandwidth of  $X/2$ ;
  - modulating a first optical carrier with the first electrical signal to generate a first optical data signal, wherein a sideband of the first optical data signal occupies a frequency band located at an offset of  $X/2$  to X from the first optical carrier;
  - receiving a second electrical signal with a bandwidth of  $X/2$ ;
  - modulating a second optical carrier with the second electrical signal to generate a second optical data signal, wherein a sideband of the second optical data signal occupies a frequency band located at an offset of  $X/2$  to X from the second optical carrier, and the first optical carrier and the second optical carrier are located at different frequencies; and
  - optically combining the first optical data signal and the second optical data signal to generate a composite optical signal with a bandwidth of approximately X and containing the sideband of the first optical data signal and the sideband of the second optical data signal.
2. The method of claim 1 wherein each of the electrical signals includes a plurality of QPSK modulated subcarriers.
3. The method of claim 2 wherein an aggregate data rate of the electrical signals is approximately X Gbps.
4. The method of claim 1 wherein X is approximately 40 GHz.
5. The method of claim 4 wherein, within the composite optical signal, the sideband of the first optical data signal and the sideband of the second optical data signal are separated by a guard band having a width of less than 4 GHz.

6. The method of claim 4 wherein, within the composite optical signal, the sideband of the first optical data signal and the sideband of the second optical data signal are separated by a guard band having a width of less than 2 GHz.
7. The method of claim 1 wherein the first optical data signal and the second optical data signal are orthogonally polarized.
8. The method of claim 1 wherein, within the composite optical signal, the sideband of the first optical data signal and the sideband of the second optical data signal are separated by a guard band having a width of less than 10% of X.
9. The method of claim 1 wherein, within the composite optical signal, the sideband of the first optical data signal and the sideband of the second optical data signal are separated by a guard band having a width that is substantially less than X.
10. A method for receiving an optical data signal comprising:  
receiving an optical data signal, wherein the optical data signal includes a  
component containing data;  
receiving an optical local oscillator signal; and  
mixing the optical data signal with the optical local oscillator signal to heterodyne  
detect the component, wherein the detected component occupies less than  
one octave of frequency.
11. The method of claim 10 wherein the detected component falls within a frequency  
band located between 20 GHz and 40 GHz.
12. A method for receiving an optical data signal comprising:  
receiving an optical data signal, wherein the optical data signal includes a single  
sideband located at a frequency offset of  $+\Delta f$  with respect to an optical local  
oscillator signal;  
optically filtering the optical data signal to attenuate noise located at a frequency  
offset of  $-\Delta f$  with respect to the optical local oscillator signal; and  
detecting the filtered optical data signal.

13. A method for generating a composite optical signal for use in an optical system having predefined frequency bands for transmissions, the method comprising:  
generating a first optical data signal containing first data;  
generating a second optical data signal containing second data; and  
optically combining the first optical data signal and the second optical data signal to generate a composite optical signal, wherein the composite optical signal occupies a single one of the predefined frequency bands.
14. The method of claim 13 wherein:  
the predefined frequency band has a center frequency;  
the first optical data signal is offset by an amount  $+\Delta f$  relative to the center frequency; and  
the second optical data signal is offset by an amount  $-\Delta f$  relative to the center frequency.
15. The method of claim 13 wherein the predefined frequency bands are defined according to the ITU grid.
16. A bidirectional optical communications system comprising:  
two transceivers, each transceiver having an optical data input and an optical data output wherein the optical data output of each transceiver is coupled to the optical data input of the other transceiver, each transceiver comprising at least one transmitter-receiver pair, each transmitter-receiver pair comprising:  
a laser source for generating a laser beam;  
an optical splitter coupled to the laser source for splitting the laser beam into a source beam and a local oscillator beam;  
an optical transmitter coupled to receive the source beam from the optical splitter for modulating the source beam with a received electrical data signal to generate an optical data signal; and  
a heterodyne receiver coupled to receive the local oscillator beam from the optical splitter for recovering an electrical data signal from an optical data signal using the local oscillator beam as an optical local oscillator in a heterodyne detection process.

17. The bidirectional optical communications system of claim 16 wherein, for each transmitter-receiver pair in each transceiver, a wavelength of the laser beam generated by that transmitter-receiver pair is locked without using a laser beam from the other transceiver.
18. The bidirectional optical communications system of claim 16 wherein:  
one of the two transceivers is a master transceiver and the other transceiver is a slave transceiver; and  
each transmitter-receiver pair in the slave transceiver further comprises:  
a wavelength locking device for wavelength locking the laser beam  
generated by that transmitter-receiver pair with the optical data signal  
received by that transmitter-receiver pair.
19. The bidirectional optical communications system of claim 18 wherein one of the transceivers is manually configured to function as the master transceiver.
20. The bidirectional optical communications system of claim 18 wherein each transceiver determines whether it is the master transceiver or the slave transceiver without communicating with the other transceiver.
21. The bidirectional optical communications system of claim 18 wherein the two transceivers negotiate which is the master transceiver and which is the slave transceiver.
22. The bidirectional optical communications system of claim 21 wherein:  
the optical data input and optical data output of one transceiver are coupled to the  
optical data input and optical data output of the other transceiver by at least  
one optical fiber;  
during normal operation, the two transceivers transmit data to each other using a  
communications channel carried on the optical fiber; and  
the negotiation occurs over a communications channel also carried on the optical  
fiber but which is more robust than the communications channel for  
transmitting data during normal operation.

23. The bidirectional optical communications system of claim 22 wherein the negotiation occurs during set up of the communications channel for transmitting data during normal operation.
24. The bidirectional optical communications system of claim 16 wherein each transmitter-receiver pair further comprises:
- an FDM multiplexer for FDM multiplexing a plurality of received electrical channels to generate the electrical data signal, the electrical data signal further including a tone.
25. The bidirectional optical communications system of claim 16 wherein:
- each transceiver comprises:
    - at least two transmitter-receiver pairs; and
    - an optical combiner coupled to the optical transmitters in the transmitter-receiver pairs for optically combining the optical data signals generated by each optical transmitter; and
  - at least one of the transceivers comprises:
    - a wavelength-locking device for wavelength-locking the laser beams generated by the transmitter-receiver pairs in that transceiver.
26. The bidirectional optical communications system of claim 16 wherein each transceiver comprises:
- a first transmitter-receiver pair having a first optical transmitter;
  - a second transmitter-receiver pair having a second optical transmitter, wherein the first optical transmitter and the second optical transmitter generate optical data signals with different polarizations; and
  - an optical combiner coupled to the optical transmitters for optically combining the optical data signals generated by each optical transmitter.
27. The bidirectional optical communications system of claim 26 wherein:
- the first optical transmitter generates a first optical data signal containing at least two subbands of information and a tone, the first optical data signal having a capacity of approximately 20 Gbps of information; and

the second optical transmitter generates a second optical data signal containing at least two subbands of information and a tone, the second optical data signal having a capacity of approximately 20 Gbps of information, wherein the second optical data signal is orthogonally polarized to the first optical data signal.

28. A transceiver comprising:  
a transmitter-receiver pair comprising:
  - a laser source for generating a laser beam;
  - an optical splitter coupled to the laser source for splitting the laser beam into a source beam and a local oscillator beam;
  - an optical transmitter coupled to receive the source beam from the optical splitter for modulating the source beam with a received electrical data signal to generate an optical data signal; and
  - a heterodyne receiver coupled to receive the local oscillator beam from the optical splitter for recovering an electrical data signal from the optical data signal using the local oscillator beam as an optical local oscillator in a heterodyne detection process.
29. The transceiver of claim 28 wherein a wavelength of the laser beam is locked without using a laser beam received from another transceiver.
30. The transceiver of claim 29 wherein the transmitter-receiver pair further comprises:
  - an etalon coupled to the laser source, the etalon having a predetermined spectral response wherein the wavelength of the laser beam is locked based on an interaction of the laser beam with the etalon.
31. The transceiver of claim 28 wherein the transmitter-receiver pair further comprises:
  - a wavelength locking device coupled to the laser source for wavelength locking the laser beam with an optical data signal received from another transceiver.
32. The transceiver of claim 28 wherein the transceiver is manually configured to function either as a master transceiver or a slave transceiver.

33. The transceiver of claim 28 wherein the transceiver determines whether it is a master transceiver or a slave transceiver without communicating with other transceivers.
34. The transceiver of claim 28 wherein the transceiver negotiates with a second transceiver whether it is a master transceiver or a slave transceiver.
35. The transceiver of claim 34 wherein:  
during normal operation, the transceiver transmits data to the second transceiver  
using a communications channel carried on the optical fiber; and  
the negotiation occurs over a separate communications channel also carried on the  
optical fiber but which is more robust than the communications channel for  
transmitting data during normal operation.
36. The transceiver of claim 35 wherein the negotiation occurs during set up of the  
communications channel for transmitting data during normal operation.
37. The transceiver of claim 28 wherein the transmitter-receiver pair further comprises:  
an FDM multiplexer coupled to the optical transmitter for FDM multiplexing a  
plurality of received electrical channels to generate the electrical data signal,  
the electrical data signal further including a tone.
38. The transceiver of claim 37 wherein the electrical channels comprise QPSK  
modulated data.
39. The transceiver of claim 28 further comprising:  
a second transmitter-receiver pair; and  
an optical combiner coupled to the optical transmitters in the transmitter-receiver  
pairs for optically combining the optical data signals generated by each  
optical transmitter.
40. The transceiver of claim 39 wherein:  
the optical transmitter of each transmitter-receiver pair generates an optical data  
signal at a different wavelength; and  
the optical combiner includes a WDM multiplexer.

41. The transceiver of claim 39 wherein:  
the optical transmitter of each transmitter-receiver pair generates an optical data signal with a different polarization; and  
the optical combiner includes a polarized beam combiner.
42. The transceiver of claim 39 wherein:  
the optical transmitter of the first transmitter-receiver pair generates a first optical data signal containing at least two subbands of information and a tone, the first optical data signal having a capacity of approximately 20 Gbps of information; and  
the optical transmitter of the second transmitter-receiver pair generates a second optical data signal containing at least two subbands of information and a tone, the second optical data signal having a capacity of approximately 20 Gbps of information, wherein the second optical data signal is orthogonally polarized to the first optical data signal.
43. A method for transmitting and receiving data across a bidirectional optical communications system, the method comprising:  
generating a laser beam;  
splitting the laser beam into a source beam and a local oscillator beam;  
receiving a first electrical data signal;  
modulating the source beam with the first electrical data signal to generate a first optical data signal;  
receiving a second optical data signal; and  
recovering a second electrical data signal from the second optical data signal using the local oscillator beam as an optical local oscillator in a heterodyne detection process.
44. The method of claim 43 further comprising:  
wavelength locking the laser beam without using the second optical data signal.
45. The method of claim 43 further comprising:  
wavelength locking the laser beam with the second optical data signal.

46. The method of claim 43 further comprising:  
manually configuring the laser beam to function either as a master or a slave.
47. The method of claim 43 further comprising:  
determining locally whether the laser beam is to function as a master or a slave.
48. The method of claim 43 further comprising:  
negotiating whether the laser beam is to function as a master or a slave.
49. The method of claim 48 wherein:  
during normal operation, the second optical data signal is received using a  
communications channel carried on an optical fiber; and  
negotiating whether the laser beam is to function as a master or a slave occurs over a  
separate communications channel also carried on the optical fiber but which  
is more robust than the communications channel used during normal  
operation.
50. The method of claim 49 wherein negotiating whether the laser beam is to function as  
a master or a slave occurs during set up of the communications channel used during normal  
operation.
51. The method of claim 43 further comprising:  
receiving a plurality of electrical channels; and  
FDM multiplexing the plurality of electrical channels to generate the first electrical  
data signal, the first electrical data signal further including a tone.
52. The method of claim 43 further comprising:  
generating a third optical data signal; and  
optically combining the first optical data signal and the third optical data signal.
53. The method of claim 52 wherein:  
the first optical data signal is located at a first wavelength;  
the third optical data signal is located at a third wavelength different from the first  
wavelength; and

optically combining the first optical data signal and the third optical data signal comprises WDM multiplexing the first optical data signal and the third optical data signal.

54. The method of claim 52 wherein:  
the first optical data signal has a first polarization;  
the third optical data signal has a third polarization different from the first polarization; and  
optically combining the first optical data signal and the third optical data signal comprises optically combining the first optical data signal and the third optical data signal based on polarization.
55. The method of claim 52 wherein:  
the first optical data signal contains at least two subbands of information and a tone, the first optical data signal having a capacity of approximately 20 Gbps of information; and  
the third optical data signal contains at least two subbands of information and a tone, the third optical data signal having a capacity of approximately 20 Gbps of information, wherein the third optical data signal is orthogonally polarized to the first optical data signal.
56. A method for wavelength locking two laser sources to an etalon, the method comprising:  
wavelength locking a first laser source to a first frequency, wherein the first frequency is defined relative to a peak frequency at which an etalon has a peak spectral response and the first laser source is wavelength locked to the first frequency using the etalon; and  
wavelength locking a second laser source to a second frequency, wherein the first frequency and the second frequency differ by an amount that is less than twice a frequency period of the spectral response of the etalon.
57. The method of claim 56 wherein:  
one of the first and second frequencies is greater than the peak frequency; and  
the other of the first and second frequencies is less than the peak frequency.

58. The method of claim 57 wherein the first and second frequencies are symmetrically disposed to either side of the peak frequency.

59. The method of claim 56 wherein wavelength locking the second laser source comprises:

wavelength locking the second laser source to the first laser source.

60. The method of claim 59 wherein wavelength locking the second laser source comprises:

wavelength locking the second laser source to the first laser source using a phase locked loop.

61. The method of claim 56 wherein the second frequency is defined relative to the peak frequency and the second laser source is wavelength locked to the second frequency using the etalon.

62. A method for wavelength locking two laser sources to an etalon, the method comprising:

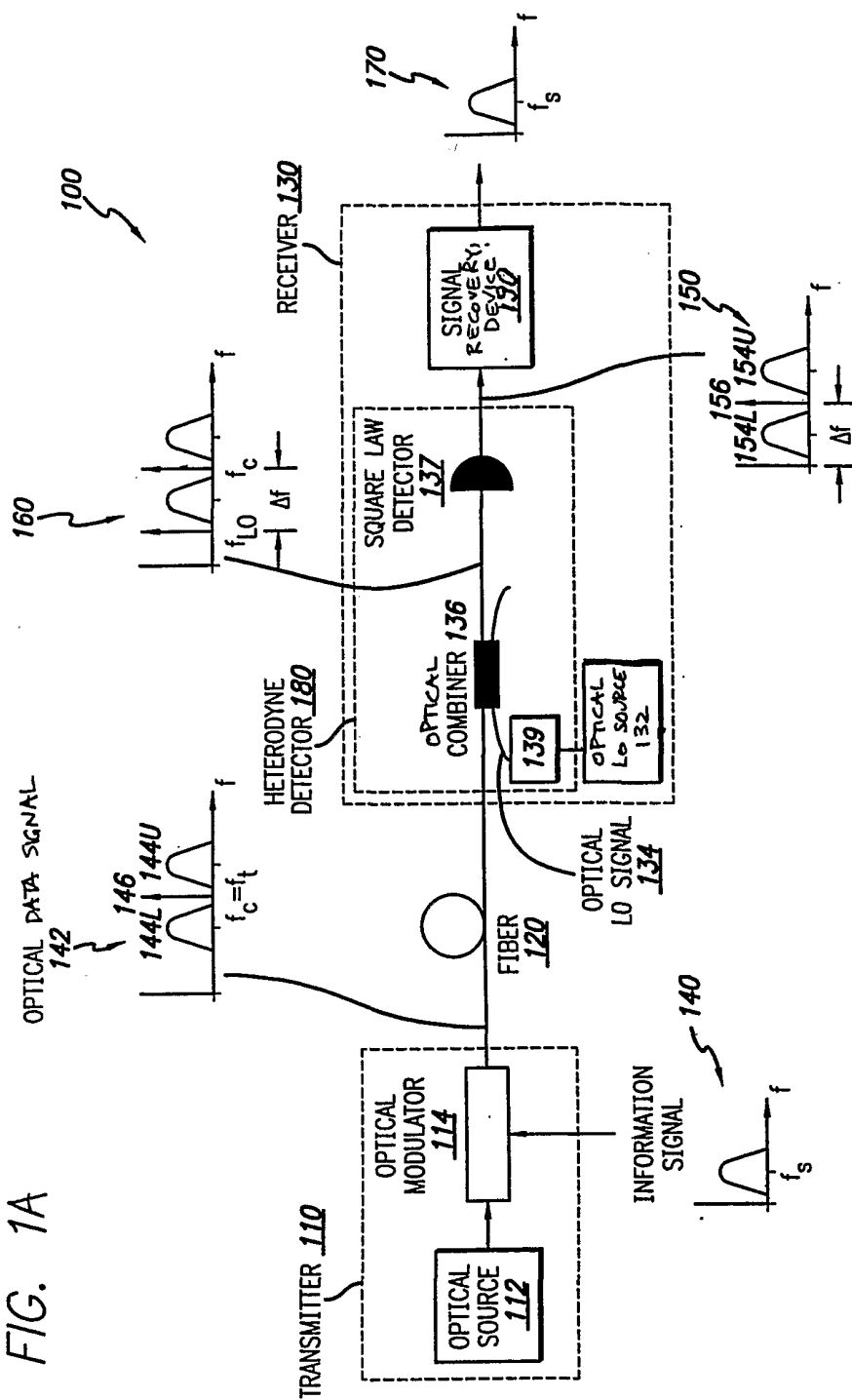
wavelength locking a first laser source to a first frequency, wherein the first frequency is defined relative to a peak frequency at which an etalon has a peak spectral response and the first laser source is wavelength locked to the first frequency using the etalon; and

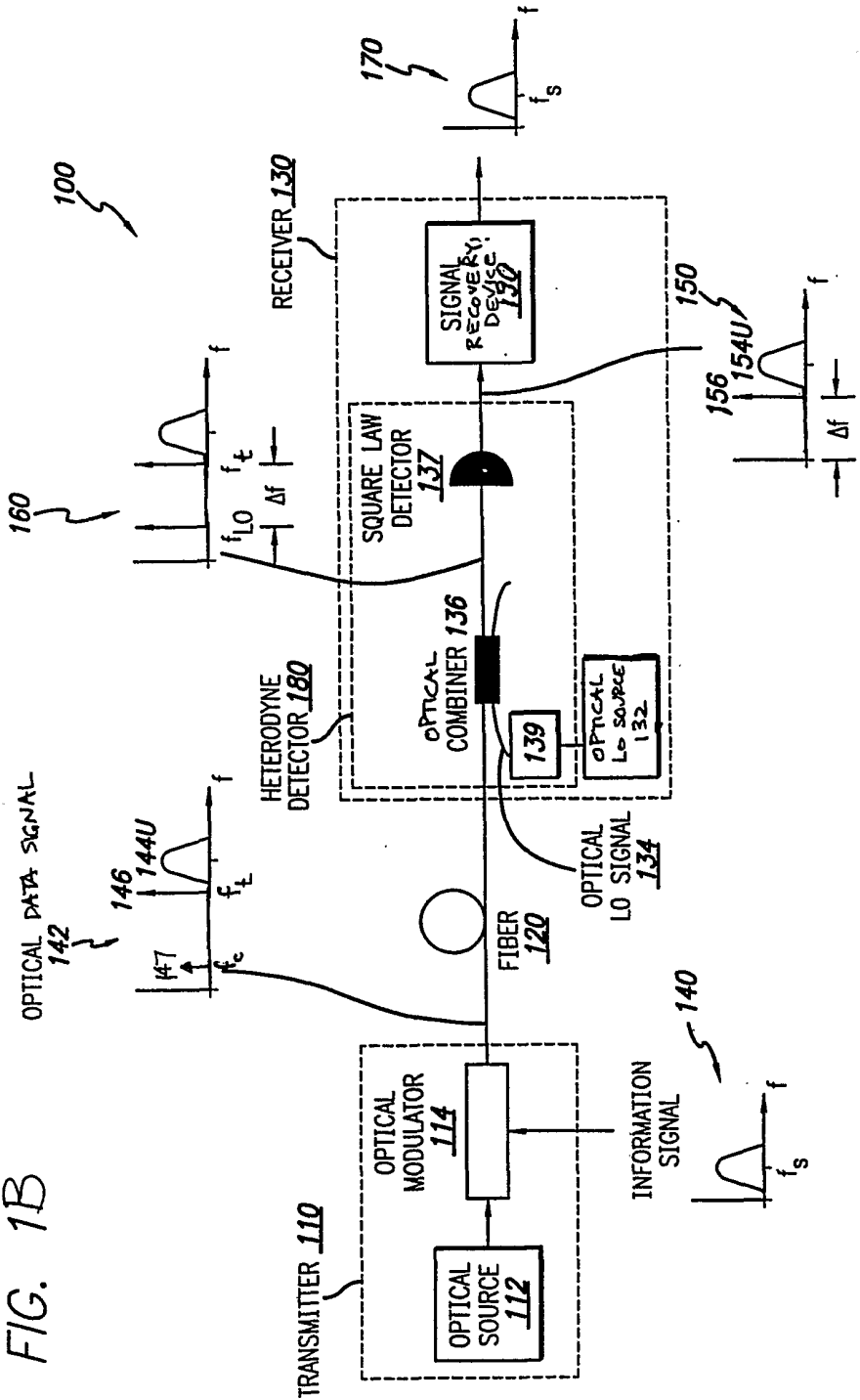
wavelength locking a second laser source to a second frequency, wherein the second frequency is defined relative to the first frequency.

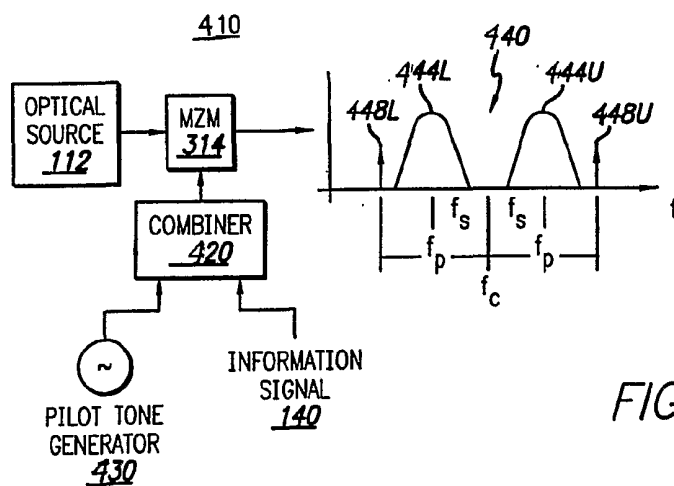
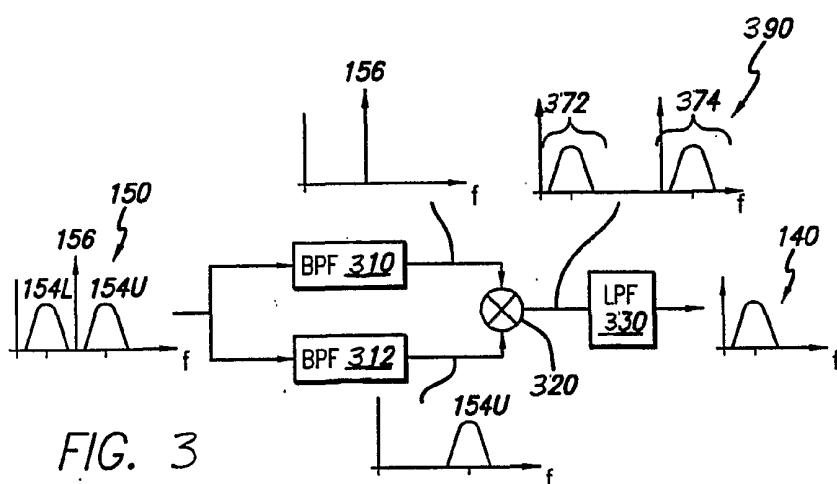
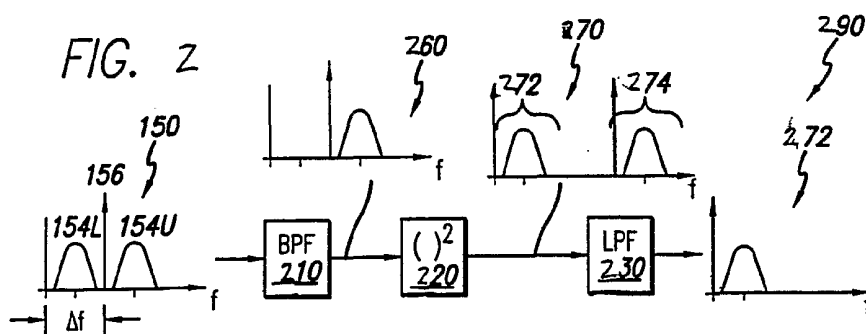
63. The method of claim 62 wherein wavelength locking the second laser source comprises:

wavelength locking the second laser source to the first laser source using a phase locked loop.

FIG. 1A







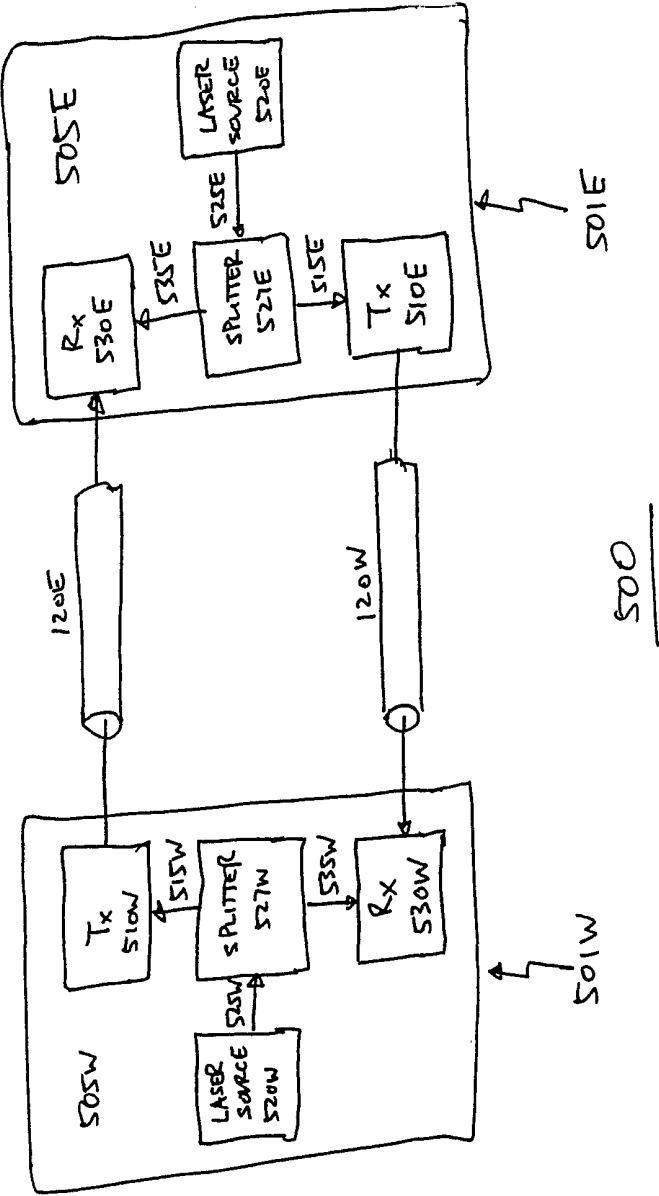


FIG. 5

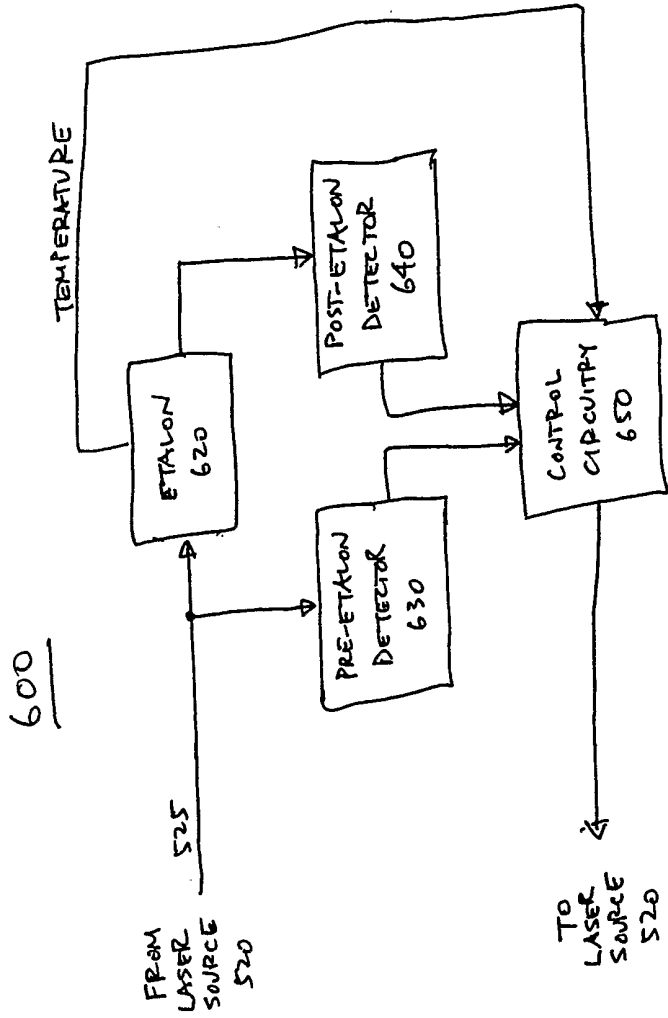


FIG. 6A

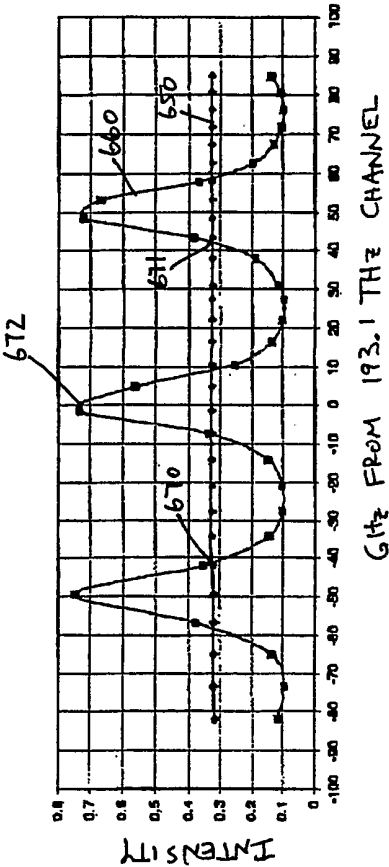


FIG. 6B

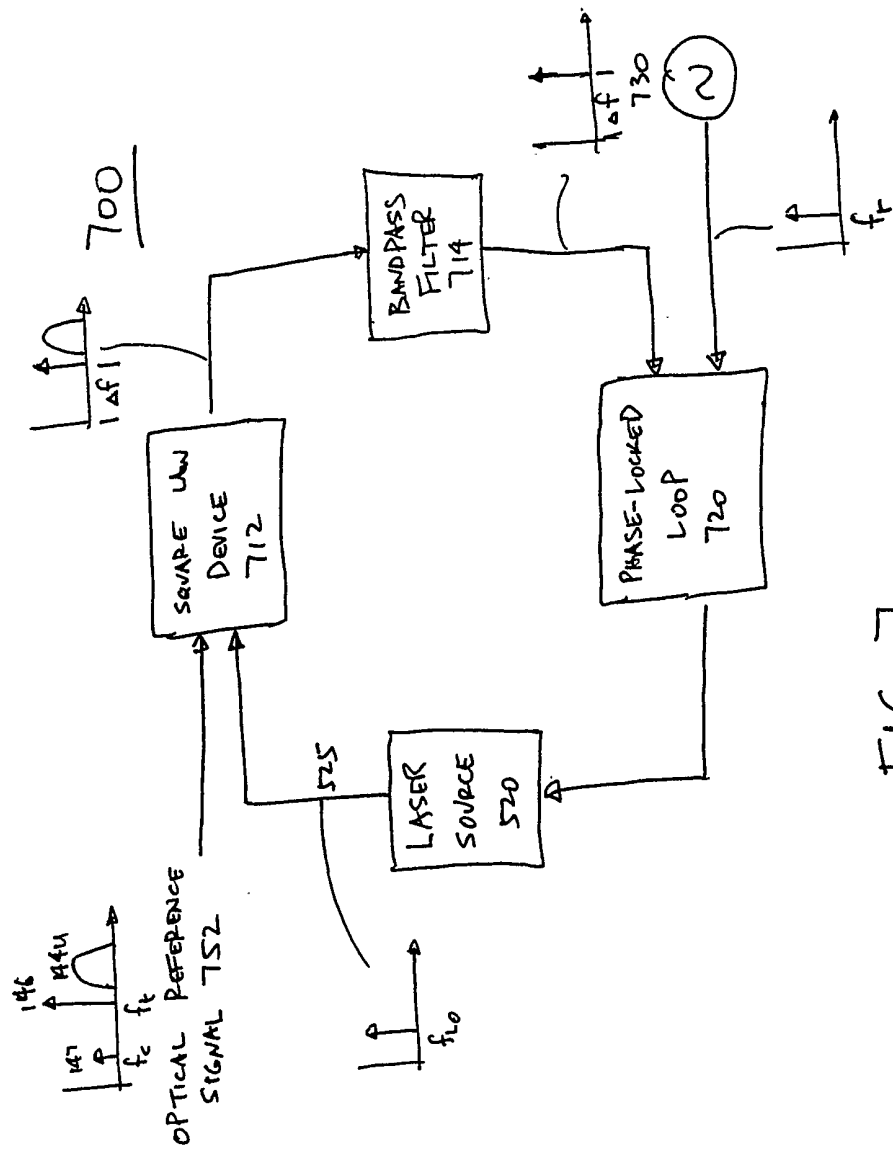
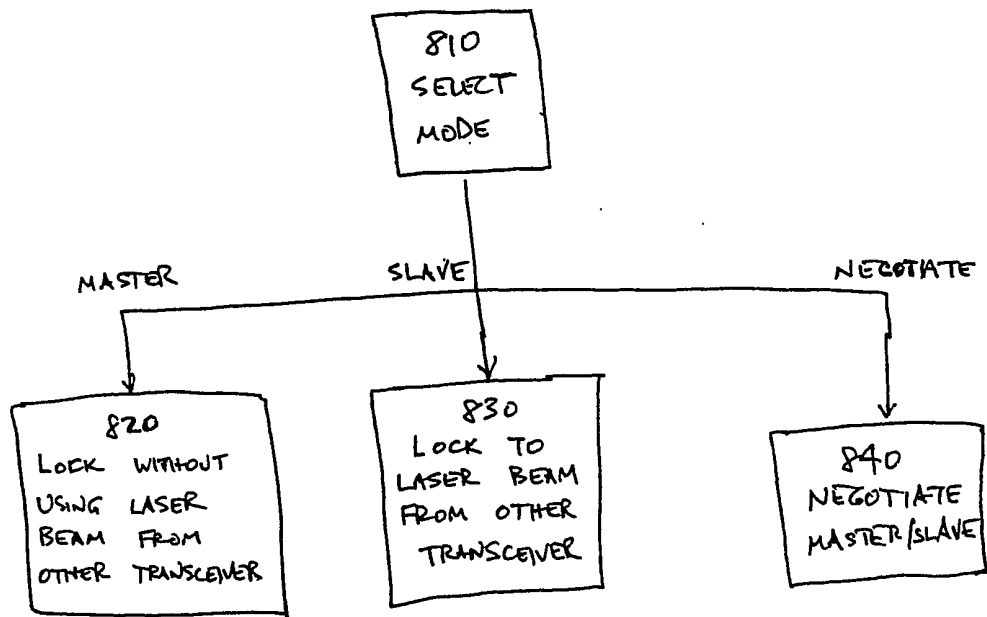


FIG. 7



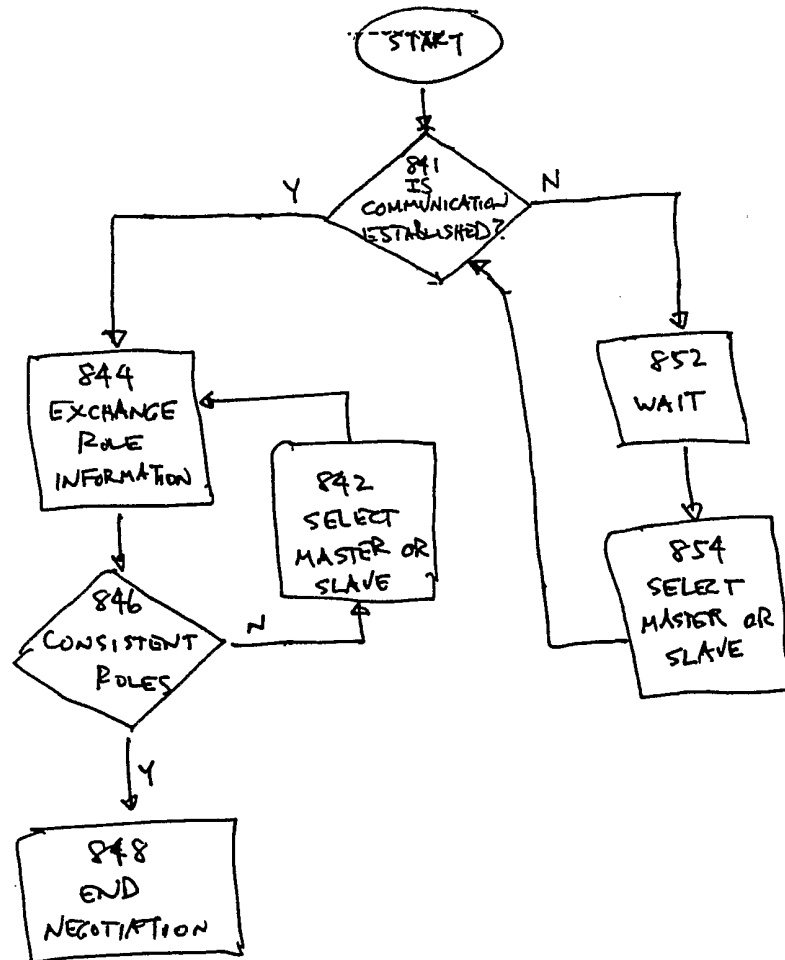


FIG. 8B

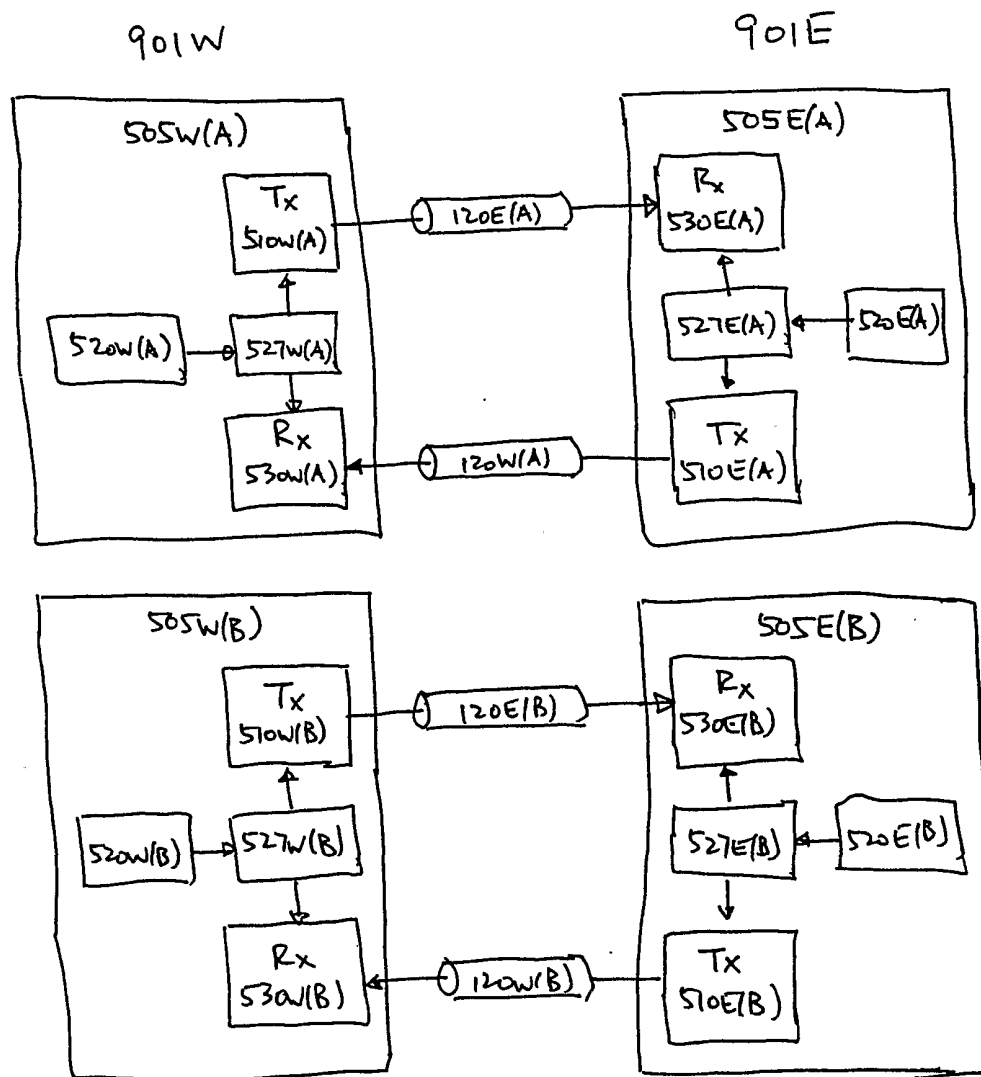


FIG. 9

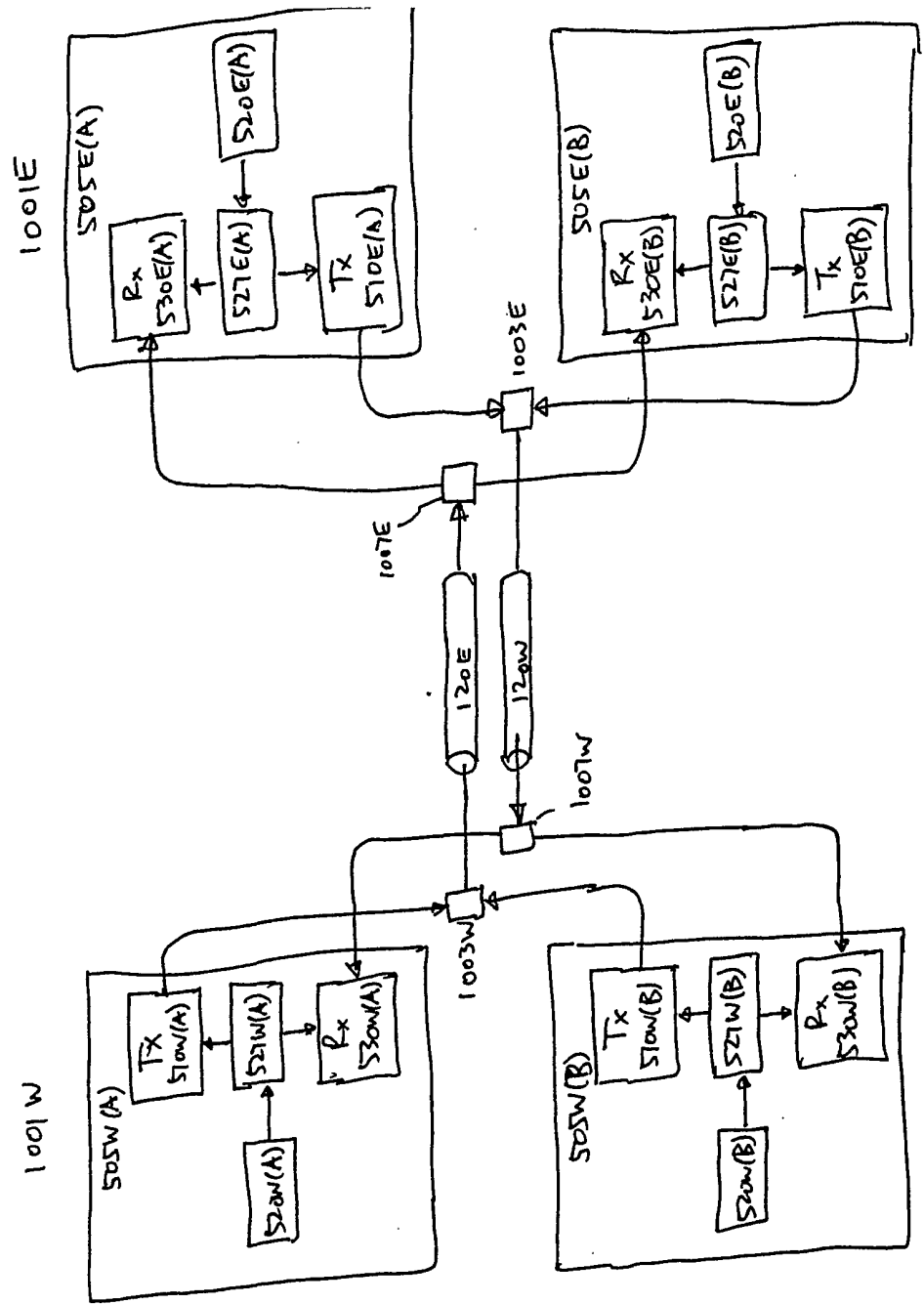


FIG. 10

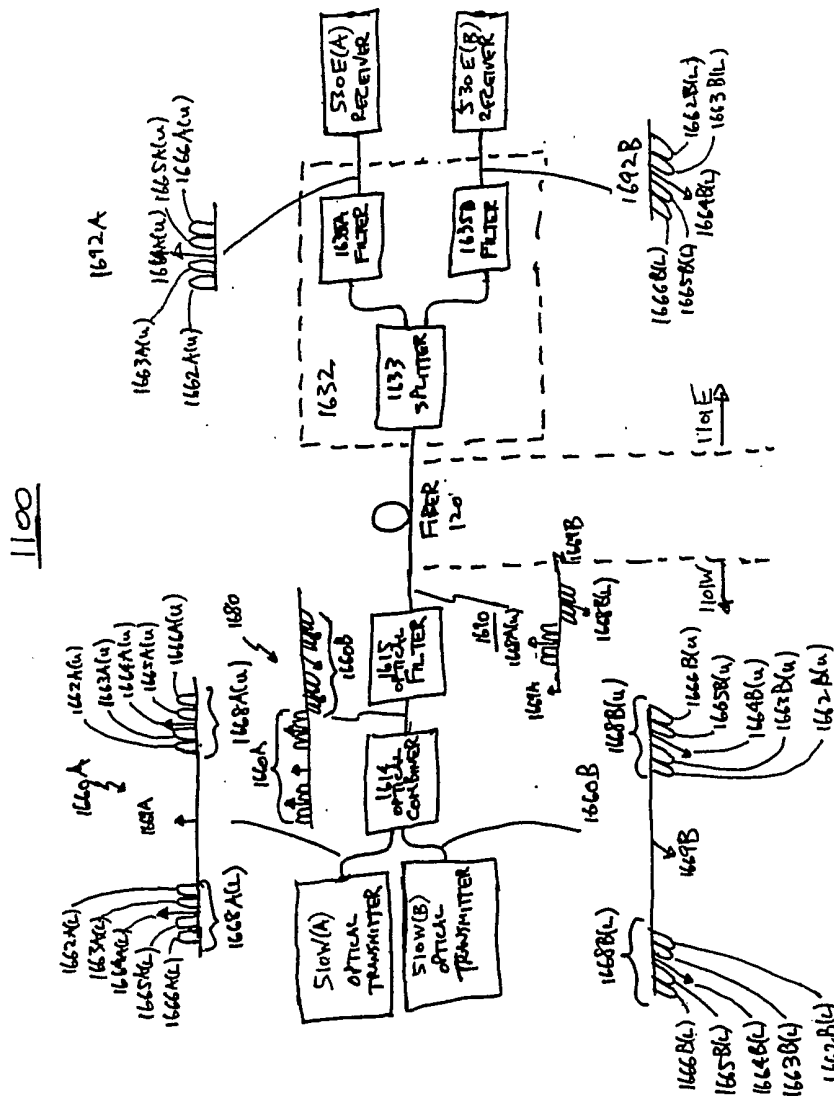


FIG. 11

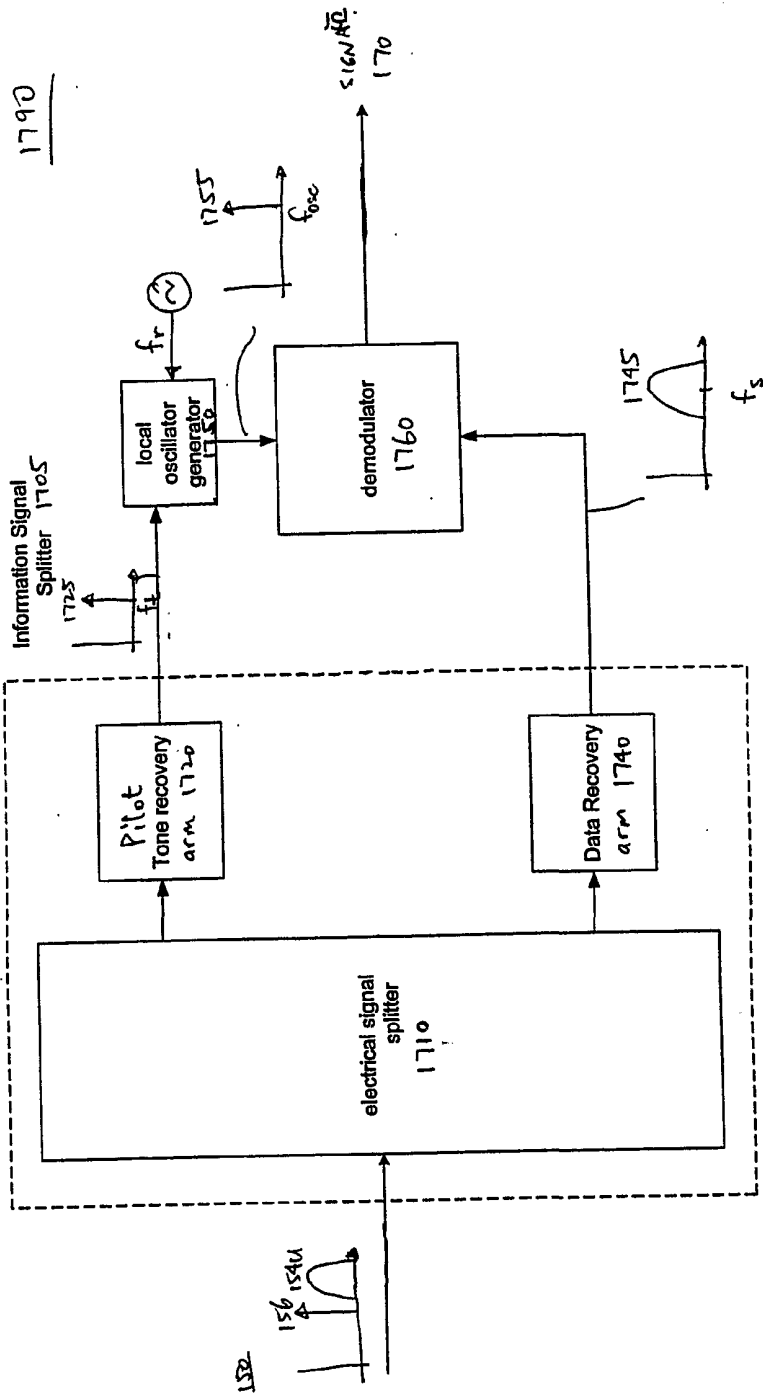


Figure 12