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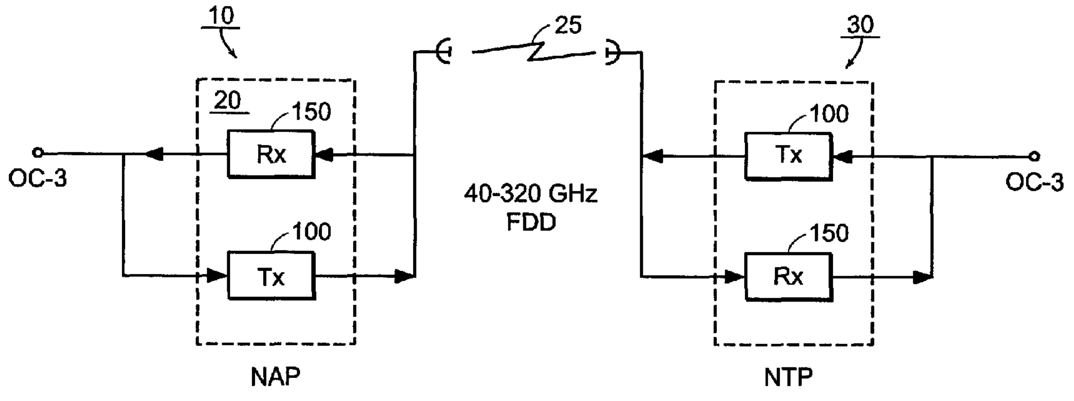
(54) **Title:** OPTICAL TO MICROWAVE CONVERTER USING DIRECT MODULATION



(57) **Abstract:** A point-to-point microwave radio link that operates in a Frequency Division Duplex (FDD) mode using direct digital modulation (25). The direct digital modulation (25) may be Frequency Shift Keyed (FSK), On-Off Keyed (OOK), or Phase Shift Keyed (PSK). The transmit signal is generated by a circuit that uses a Voltage-Control Oscillator (VCO) operating in a microwave radio band to obtain the modulated signal. The output of the VCO is then frequency multiplied by the predetermined factor to produce the modulated microwave output signal directly on the desired microwave band.

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OPTICAL TO MICROWAVE CONVERTER USING DIRECT MODULATION

BACKGROUND OF THE INVENTION

The need to transport high-bandwidth signals from place to place continues to drive growth in the telecommunications industry. As the demand for high-speed access to data networks, including both the Internet and private networks, continues to evolve, network managers face an increasing need to transport data signals over short distances. For example, in corporate campus environments, it is often necessary to implement high-speed network connections between buildings rapidly and inexpensively, without incurring commitments for long-term service contracts with local telephone companies. Other needs occur in residential areas, including apartment buildings, and even private suburban neighborhoods. Each of these settings requires efficient distribution of high-speed data signals to a number of locations.

An emerging class of products provides a broadband wireless access solution via point-to-point communication links over radio carrier frequencies in the microwave radio band. The telecommunications transport signals may be provided on a wire, but increasingly, these are provided on optical fiber media. An optical to electrical conversion stage is thus first required to convert the baseband digital signal. Next, a microwave frequency radio is needed to up-convert the broadband digital signal to a suitable radio carrier frequency. These up-converters are typically implemented using multi-stage heterodyne receivers and transmitters such that the input baseband signal is modulated and then up-converted to the desired radio frequency. In the case of an OC-3 rate optical transport signal having a bandwidth of 155 MegaHertz (MHz), the input signal may be up converted to an ultimate microwave carrier of, for example, 23 GHz, through several Intermediate Frequency (IF) stages at lower radio frequencies.

Other implementations may use optical technologies to transport the signal over the air. These technologies use optical emitters and detectors operating in the high infrared range. While this approach avoids conversion of the optical input to an electrical signal, it has certain limitations. First, the light wave carrier has a narrow beamwidth, meaning that the transmitter and receiver must be carefully aligned with one another. Light wave carriers are also more susceptible to changes in physical conditions. These changes may be a result of changes in sunlight and shade exposure, or foreign material causing the lenses to become dirty over time. Other problems may occur due to vibrations from nearby passing automobiles and heating ventilating and cooling equipment. Some members of the public are concerned with possible eye damage from high powered lasers.

SUMMARY OF THE INVENTION

The present invention is a point-to-point microwave radio link that operates in a Frequency Division Duplex (FDD) mode using separate microwave band radio frequency carriers for each direction. The transmitter uses direct digital modulation to convert an input baseband optical rate signal to the desired microwave frequency carrier. The design may be targeted for operation at unallocated carrier frequencies in the millimeter wave spectrum, such from 40-320 GHz.

While the direct digital modulation approach is not necessarily bandwidth-efficient, it provides a low cost alternative to traditional approaches, since the base band modem and multiple RF stages are eliminated. Because there are no heterodyne stages, there also are no images of the modulated baseband signals created on either side of the carrier frequency. Thus, image reject filters are not necessary.

Direct digital modulation also only creates modulation artifacts at high multiples of the VCO center frequency. This allows the output bandpass filters to be implemented using inexpensive waveguide technologies that can easily reject the harmonics of the VCO output, as opposed to more stringent filters that might otherwise be required to reject the harmonics of the baseband signal.

In a first embodiment, the direct digital modulation mechanism is implemented using a Continuous Phase-Frequency Shift Keyed (CP-FSK) scheme. The CP-FSK signal is generated at the transmitter by a circuit that uses a stable voltage controlled oscillator (VCO) operating in the 10-13 GHz band. The VCO is deviated over a narrow frequency range, such as 10-20 MHz. The narrow deviation range need only be a fraction of the ultimately desired deviation range of the microwave carrier, because of the use of a frequency multiplier. In particular, the VCO output is fed to a frequency multiplier that multiplies the modulated microwave signal output to a higher output carrier frequency. A bandpass filter and power amplifier then feed a final stage filter and antenna.

The deviation frequency of the CP-FSK modulator is thus chosen to be the reciprocal of the multiplication factor implemented by the frequency multiplier times the desired bit rate. For example, where it is desired to generate an output microwave signal in the 48-52 GHz range for a OC-3 input optical signal, the frequency multiplier may multiply the oscillator output by a factor of four. In this instance the frequency deviation chosen for the direct digital modulator is therefore equal to the input data rate divided by four. In the case of an input OC-3 rate digital data signal, the input data rate is 155.22 Megabits per second (Mbps), meaning that the required VCO deviation is therefore 38.88 MHz. In a case where a frequency multiplication factor of eight is introduced in the output signal processing chain, the VCO deviation may be further reduced accordingly.

The CP-FSK receiver uses a similar but inverse signal chain consisting of a microwave oscillator, frequency multiplier, and bandpass filter. A single down conversion stage is all that is required. By inserting the frequency multiplier between the oscillator and down convertor mixer, the local oscillator remains offset by a wide margin from the input RF carrier frequency. This permits the receiver image reject filters to be implemented more easily.

In a second embodiment, the direct digital modulation mechanism is implemented using an On-Off Keyed (OOK) scheme. The OOK signal is generated at the transmitter by a circuit that uses a stable oscillator operating in the Ku microwave band. The oscillator RF output is switched on and off using a high speed switch. The switched oscillator output is fed to a frequency multiplier that multiplies the modulated microwave signal output to a higher output carrier frequency. For example, where it is desired to generate an output microwave signal in the 48-52 GHz range for a OC-3 input optical signal, the frequency multiplier may multiply the oscillator output by a factor of four. A bandpass filter and power amplifier then feed a final stage filter and antenna.

The direct OOK receiver uses an inverse signal chain consisting of a microwave oscillator, frequency multiplier, and bandpass filter. A single down conversion stage is all that is required. By inserting the frequency multiplier between the oscillator and down convertor mixer, the local oscillator remains offset by a wide margin from the input RF carrier frequency. This permits the receiver image reject filters to be implemented more easily.

In a third embodiment, the transmitter implements direct Phase Shift Keyed (PSK) modulation using a direct coupled multiplier followed by a phase shifter. With this arrangement, the transmitter uses a stable voltage controlled oscillator operating in the 10-13 GHz band. The oscillator output is then up-converted to the desired microwave range. For operation in the 40-52 GHz range, this may be a single stage times four (x4) frequency multiplier for operation at a higher range, such as from 81-87 GHz, a second, times two (x2) multiplier may also be employed.

The frequency multiplier output feeds a phase modulator and/or attenuator circuit. In particular, the frequency multiplier output is fed to a phase modulator that deviates the phase of the multiplied output carrier by a desired amount. The phase deviator may be one or more circulators and pin switches in this preferred embodiment. A bandpass filter and power amplifier may typically be inserted prior to the phase shifter.

The direct digital modulation transmitter may also be implemented using a sub-phase implementation. In this approach, a stable voltage controlled oscillator operating in the 10-13 Giga Hertz (GHz) band is once again used. This oscillator feeds a phase modulator circuit that operates over a narrower phase range than would otherwise typically be used. For example, the phase deviation range is typically only a fraction of the ultimately desired phase deviation range of the output microwave signal. The phase modulator is thus preferably chosen so that it deviates the phase by a desired output amount divided by a particular factor.

That same particular factor is then used by an output frequency multiplier to multiply the phase modulated signal to a higher output carrier frequency. A bandpass filter and power amplifier may then be used to feed a final stage filter prior to forwarding the signal to a transmit antenna.

The phase deviation of the phase modulator in this embodiment is preferably chosen to be the reciprocal of the multiplication factor implemented by the frequency multiplier. For example, the phase modulator may implement phase shifts of 0, 22.5, 45, and 67.5 degrees when a frequency multiplier having a multiplication factor of four (4) is applied to an input 10 GHz range VCO signal. After being subjected to the multiplication body output multiplier, the desired output phases of 0, 90, 180, and 270 degrees are provided.

Likewise, in a case where a multiplication factor of 8 is introduced in the output signal processing chain, the phase deviation may be further reduced accordingly. In such an instance, where the output carrier signal generated from the 10 GHz VCO is ultimately multiplied up to a range of 80 GHz, the sub-angle phase deviations implemented by the phase modulator would be 0, 11.5, 22.5, and 33.75 degrees.

The phase modulation receiver uses a similar but inverse signal chain consisting of a microwave oscillator, frequency multiplier, and bandpass filter. A single down conversion stage is all that is required. By inserting the frequency multiplier between the oscillator and down converter mixer, the local oscillator remains offset by a wide margin from the input RF carrier frequency. This permits receiver image reject filters to be implemented more easily.

If amplitude modulation is also desired, an attenuator may be inserted in-line prior to the phase deviator. This allows multi-level modulation schemes such as Quadrature Amplitude Modulation (QAM) to be employed.

This scheme provides a low cost alternative to traditional approaches, since the base band modem and multiple RF stages are eliminated. Because there are no heterodyne stages, there also are no images of the modulated baseband signals created on either side of the carrier frequency. Thus, image reject filters are not necessary.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a block diagram of a point-to-point, optical to microwave link according to the invention.

Fig. 2 is a detailed circuit diagram of a Continuous Phase-Frequency Shift Keyed (CP-FSK) transmitter used in the link.

Fig. 3 is a detailed circuit diagram of a CP-FSK receiver that may be used.

Fig. 4 is a detailed circuit diagram of an On-Off Keyed (OOK) transmitter that may be used in the link.

Fig. 5 is a detailed circuit diagram of an OOK receiver that may be used.

Fig. 6 is a detailed circuit diagram of a direct modulation Phase Shift Keyed (PSK) transmitter that uses sub-phase deviation prior to carrier multiplication.

Fig. 7 is a detailed circuit diagram of another embodiment of a direct modulation PSK transmitter that uses post-multiplication phase modulation.

Fig. 8 is a detailed circuit diagram of a direct modulation PSK receiver.

The foregoing and other objects, features and advantages of the invention will be apparent from the following more particular description of preferred embodiments of the invention, as illustrated in the accompanying drawings in which like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention.

DETAILED DESCRIPTION OF THE INVENTION

A description of preferred embodiments of the invention follows.

Fig. 1 is a block diagram of a point-to-point wireless communications system that uses a direct conversion transmitter and receiver according to the invention. The system 10 includes at least a pair of optical-to-microwave link interfaces 20, 30. A first optical-to-microwave link interface 20 may be located, for example, at a central location such as a Network Access Point (NAP) that provides connections to a data network. In the illustrated example, the network connection is provided from an optical fiber that carriers a transport signal modulated in accordance with the OC-3 standard signaling format. The OC-3 optical signal carries an information signal having a data rate of 155.52 Megabits per second (Mbps). A similar optical-to-microwave converter unit 30 is located at another remote location, such as a Network Termination Point (NTP). The unit 30 also provides connectivity to a similar OC-3 optical transport connection. The units 20, 30 may, for example, be located on the roofs of buildings in a campus environment to which it is desired to provide high-speed network connections between buildings.

In any event, both units 20 and 30 each have a transmitter 100 and receiver 150. The transmitters 100 and receivers 150 operate in a Frequency Division Duplex (FDD) mode, such that transmitter-receiver pairs operate on distinct carrier frequencies. For example, in a downlink direction from unit 20 towards unit 30, the transmitter 100 in unit 20 operates on the same microwave carrier frequency to which the receiver 150 in unit 30 is tuned. Likewise, the receiver 150 in unit 20 is tuned to the microwave carrier which the transmitter 100 in unit 30 operates.

Acceptable operating frequencies for the uplink and downlink may be in an unlicensed microwave band. For example, in the United States, appropriate unlicensed microwave radio bands occur in the various regions of the 40 to 320 GHz band.

It should be understood that units 20 and 30 may be deployed at any short haul point-to-point locations, such that the specific locations are in effect network peers. It should also be understood that the invention may be used to carry data traffic between different types of locations and different types of network traffic.

The invention may adopt direct modulation in various ways, including at least Frequency Shift Keyed (FSK), On-Off Keyed (OOK), and Phase Shift Keyed (PSK) modulation. An exemplary embodiment for each modulation type is now discussed herein.

Turning attention to Fig. 2, an exemplary FSK transmitter 100 will be described in greater detail. The transmitter 100 includes an optical to voltage transducer 112, a baseband filter 114, a direct modulator 116, a multiplier 118, a bandpass filter 120, a buffer amplifier 122, an output waveguide filter 130, and a transmit antenna 132. Optionally, a second-stage bandpass filter 124 and multiplier 126 may be utilized. The Fig. 2 implementation is for a Continuous Phase-Frequency Shift Keyed (CP-FSK) embodiment. As will be understood shortly, the signal radiated by the transmitter 100 has a continuous phase and employs frequency modulation in order to communicate information to the receiver 150.

In operation, the input OC-3 formatted optical signal is fed to the optical to voltage transducer 112. The transducer 112 produces at its output a raw transport bitstream. For an input optical signal of the OC-3 format, the transport bitstream is a digital signal at a 155.22 Mbps rate. The raw transport bitstream is then fed to a lowpass filter 114 to remove any artifacts of the optical to voltage conversion process. It should be understood that other digital input signal types may be supported, such as OC-1, OC-12 or other optical range transport signals.

The modulator 116 is preferably a Voltage Controlled Oscillator (VCO) of the Dielectric Resonator Oscillator (DRO) type. The modulator 116 implements Continuous Phase-Frequency Shift Keyed (CP-FSK) type modulation shifting to, for example, a lower frequency to indicate a zero data bit and to a higher frequency to indicate a one data bit. The oscillator is implemented such that it preserves a continuous phase during the frequency shifts. The continuous phase nature of the oscillator further relaxes the requirements on the following filters 120, 130 and buffer amplifier 122.

After being converted to a voltage from the optical carrier, the input baseband signal is directly fed to the control input of the VCO 116. The VCO 116 provides a sub-deviated microwave carrier at its output, which shifts in frequency according to the logic state of the input signal. In the preferred embodiment, this deviation is set, however, to a relatively narrow range. For example, given an OC-3 input signal and a desired output signal in the range of 48-52 GHz, the deviation may be approximately over a range of only 38 MHz, in a carrier signal in the range of 10-13 GHz.

The sub-deviation amount is determined by the multiplication factor implemented by the following multiplier 118. In the illustrated embodiment, the multiplier 118 implements a times four multiplication of the VCO 116 output. In accordance with well-known communication theory, the spacing between the deviation frequencies in FM signals is dictated by the desired data rate. Thus, the ultimately transmitted signal must have a deviation of the desired 155.22 Mbps rate. However, the oscillators used in the VCO 116 are not particularly narrow band or stable at such high operating ranges in the 40 GHz and above range. Thus, the approach here is to use a more stable VCO 116 source at a lower range, such as in the 10-13 GHz range, and then to rely upon the multiplier 118 to shift the VCO output up to the desired operating band.

The amount of sub-deviation is thus dictated by the specific multiplication factor implemented by the multiplier 118. In the case illustrated, where the desired output deviation is 155.52 MHz, the input deviation implemented by the VCO 116 may be one-fourth of that or approximately 38.88 MHz. The output of the multiplier 118 is thus a frequency-deviated signal carrying the digital information by the microwave frequency carrier in the desired unlicensed band. In the illustrated embodiment (number 1), this carrier is 50.000 GHz, meaning that the VCO 116 is centered at 12.5 GHz.

This raw microwave signal is then fed to the first-stage bandpass filter 120 to remove artifacts of the direct modulation process. Unlike heterodyne receivers, no sidebands are created. Artifacts of the direct modulation process occur only at multiples of the 12.5 GHz VCO 116 carrier and not at image frequencies of 155.52 MHz. No RF sidebands are generated. Thus, the first-stage bandpass filter 120 need only remove the 12.5 GHz harmonics on either side of the 50 GHz carrier frequency. It therefore need not be a particularly sharp roll off filter.

A medium range buffer amplifier 122 then receives the filtered signal and forwards it to an output waveguide filter 130.

The waveguide filter 130 further reduces the harmonics of the 10 GHz oscillator 116. It need not be an image-reject filter. Such image-reject filters, if they were needed, would further increase the cost. Elimination of the heterodyne stages, while not providing as bandwidth efficient an approach, does produce a less expensive radio.

Optionally, a second-stage multiplier 126 and a bandpass filter 124 may be included for operation at higher frequencies, such as in the 81 to 87 GHz band. In example 2, the microwave carrier is 856 GHz, generated from a 10.625 GHz VCO. In this instance, the input deviation may be even smaller, since the multiplication factor is times eight. Thus, the input deviation for the OC-3 signal may be in this instance in the range of only 9.72 MHz. The point is, as before, to make the deviation implemented by the VCO 116 to be the reciprocal of the overall multiplication factor in the RF chain multiplied by the designed data rate. This ensures that after the frequency multiplication stages 118, 126, the carrier bandwidth is consistent with the data rate of the input signal.

Turning attention now to Fig. 3, an exemplary FSK receiver 150 will be described in greater detail. This receiver includes a receiving antenna 151, input waveguide filter 152, low-noise amplifier 154, bandpass filter 156, local reference generator 160, mixer 161, buffer amplifier 162, a pair of bandpass filters 163, 164, and associated detectors 165 and 167, a differential amplifier 168 and voltage-to-optical transducer 170.

The input signal provided to the receiving antenna 151 is fed to the waveguide filter 152. This filter, having a center frequency in the 50 or 85 GHz range, as the case may be, filters the desired signal from the surrounding background information.

The low-noise amplifier 154 may be implemented as a Monolithic Microwave Integrated Circuit (MMIC) feeding a planar bandpass filter in the 50 or 85 GHz range. The low noise amplifier typically has a 6-8 decibel (dB) noise figure and provides 10-20 dB of gain. The secondary filter 156 may be implemented as needed prior to the down- converter mixer stage 161.

The local oscillator reference generator 160 consists of a 12.5 GHz or 10.375 GHz oscillator 157, frequency multiplier 158 and bandpass filter 159. The arrangement chain of components is identical to that used in the transmitter, namely the modulator 116, multiplier 118, and bandpass filter 120.

The down-converter 161 uses a single mixer that provides the baseband information to a buffer amplifier 162. Thus, the resulting signal is the basic raw 155.52 MHz information modulated onto the microwave carrier output. For example, a logical bit one may be indicated by a 2.077 GHz frequency, namely 2 GHz plus one-half of 155.52 MHz and the logical one information may be associated with 1.923 GHz. Thus, the pair of bandpass filters 163 and 164 are tuned respectively to receive the frequencies indicating a data bit of zero or data bit of one, respectively.

The detector diodes 165 and 167 provide an output indication when energy is present in the output of the respective bandpass filters 163 or 164. These detected signals are then fed to the differential amplifier 168 to provide a resulting digital signal. This is then fed to the voltage-to-optical transducer 170 to reconstruct the OC-3 format optical transport signal. The center frequencies of the two filters 163 and 164 differ by 155.52 MHz.

Down-conversion directly to the relatively high IF of 2 GHz provides for a simpler discriminator implementation, i.e., the respective bandpass filters may be at a microwave frequency rather than at baseband. This results from the fact that the resulting local oscillator signal fed to the down-convertor mixer 161 is offset from the RF carrier by 2 GHz, and ensures that it is easier to reject images in the bandpass filters 163 and 164.

The invention, therefore, provides for direct modulation of the input bitstream utilizing a Continuous Phase Frequency Shift Keyed approach. No manipulation of the bitstream is required such as in the case of baseband modulation. Furthermore, because of the direct up-conversion to the desired microwave frequency carrier, multiple heterodyne stages are eliminated. Heterodyne stages, while providing for efficient filtering topologies, create interference and spurious noise problems, as well as increased cost in overall implementation.

By modulating the carrier source, such as provided by a voltage-control oscillator at a deviation frequency less than the desired baud rate by a factor of 1/n, with n being the multiplication factor in the up-conversion chain, the overall design is greatly simplified. Standard microwave component building blocks can be used in a highly-producible assembly as a result.

Turning attention now to Fig. 4, an exemplary transmitter 100 for an On-Off Keyed (OOK) type modulation will be described in greater detail. The transmitter 100 includes an optical to voltage transducer 112, a baseband filter 114, an oscillator 116, a direct modulator 117, a multiplier 118, a bandpass filter 120, a buffer amplifier 122, an output waveguide filter 130, and a transmit antenna 132. Optionally, a second-stage bandpass filter 124 and multiplier 126 may be utilized.

In operation, the input OC-3 formatted optical signal is fed to the optical to voltage transducer 112. The transducer 112 produces at its output a raw transport bitstream. For an input optical signal of the OC-3 format, the transport bitstream is a digital signal at a 155.22 Mbps rate. The raw transport bitstream is then fed to a lowpass filter 114 to remove any artifacts of the optical to voltage conversion process. It should be understood that other digital input signal types may be supported, such as OC-1, OC-12 or other optical range transport signals.

The oscillator 116 is perferably a phase-locked fixed frequency oscillator in combination with a high speed switch. The switch 117 implements On-Off Keyed

(OOK) type modulation shifting to, for example, switch off to indicate a zero data bit and switch on to indicate a one data bit.

After being converted to a voltage from the optical carrier, the input baseband signal is directly fed to the control input of the switch 117.

The oscillators used in the oscillator 116 are not particularly narrow band or stable at high operating frequencies in the 40 GHz and above range. Thus, the approach here is to use a more stable oscillator 116 source at a lower range, such as in the Ku Band, and then to rely upon the multiplier 118 to shift the oscillator output up to the desired operating band.

The output of the multiplier 118 is an amplitude-modulated signal carrying the digital information by the microwave frequency carrier in the desired unlicensed band. In the illustrated embodiment of Fig. 4, this carrier is 50.000 GHz, meaning that the oscillator 116 is centered at 12.5 GHz.

This raw microwave signal is then fed to the first-stage bandpass filter 120 to remove artifacts of the direct modulation process.

A buffer amplifier 122 then receives the filtered signal and forwards it to an output waveguide filter 130.

The waveguide filter 130 further reduces the harmonics of the oscillator 116. It need not be an image-reject filter. Such image-reject filters, if they were needed, would further increase the cost. Elimination of the heterodyne stages, while not providing as bandwidth efficient an approach, does produce a less expensive radio.

Optionally, a second-stage multiplier 126 and a bandpass filter 124 may be included for operation at higher frequencies, such as in the 81 to 87 GHz band. In example 2, the microwave carrier is 85.6 GHz, generated from a 10.625 GHz VCO.

Turning attention now to Fig. 5, an exemplary OOK receiver 150 will be described in greater detail. This receiver includes a receiving antenna 151, input waveguide filter 152, low-noise amplifier 154, bandpass filter 156, local reference generator 160, mixer 161, buffer amplifier 162, a bandpass filter 163 and associated detectors 165 and 167, an amplifier 168 and voltage-to-optical transducer 170.

The input signal provided to the receiving antenna 151 is fed to the waveguide filter 152. This filter, having a center frequency in the 50 or 85 GHz range, as the case may be, filters the desired signal from the surrounding background information.

The low-noise amplifier 154 may be implemented as a Monolithic Microwave Integrated Circuit (MMIC) feeding a planar bandpass filter in the 50 or 85 GHz range. The low noise amplifier typically has a 6-8 decibel (dB) noise figure and provides 10-20 dB of gain. The secondary filter 156 may be implemented as needed prior to the down- converter mixer stage 161.

The local oscillator reference generator 160 consists of a 12.5 GHz or 10.375 GHz oscillator 157, frequency multiplier 158 and bandpass filter 159. The order of components is identical to that used in the transmitter, namely the modulator 116, multiplier 118, and bandpass filter 120.

The down-converter 161 uses a single mixer that provides the baseband information to a buffer amplifier 162. Thus, the resulting signal is the basic raw 155.52 MHz information modulated onto the microwave carrier output. The bandpass filter 163 is tuned to receive the frequency bandwidth of the modulated carrier.

The detector diode 165 provides an output indication when energy is present in the output of the bandpass filter 163. This detected signal is then fed to the amplifier 168 to provide a resulting digital signal. This is then fed to the voltage-to-optical transducer 170 to reconstruct the OC-3 format optical transport signal.

Down-conversion directly to the relatively high IF of 2 GHz provides for a simpler discriminator implementation, i.e., the bandpass filter may be at a microwave frequency rather than at baseband. This results from the fact that the resulting local oscillator signal fed to the down-convertor mixer 161 is offset from the RF carrier by 2 GHz, and ensures that it is easier to reject images in the bandpass filter 163.

The invention, therefore, provides for direct modulation of the input bitstream utilizing On-Off keying. No manipulation of the bitstream is required such as in the case of baseband modulation. Furthermore, because of the direct up-conversion to the desired microwave frequency carrier, multiple heterodyne stages are eliminated. Heterodyne stages, while providing for efficient filtering topologies, create interference and spurious noise problems, as well as increased cost in overall implementation.

Fig. 6 illustrates a Phase Shift Keyed (PSK) embodiment of the transmitter 100 will be described in greater detail. The transmitter 100 includes an optical to voltage transducer 112, a baseband filter 114, and a direct phase modulator 116. The circuit also utilizes a multiplier 118, a bandpass filter 120, a buffer amplifier 122, an output waveguide filter 130, and a transmit antenna 132. Optionally, a second-stage bandpass filter 124 and multiplier 126 may be utilized.

The direct phase modulator 116 includes a data formatting integrated circuit (IC) 141, a pair of buffers 142-1, 142-2, a local oscillator 144, a phase shifter 145, a pair of phase modulators 146-1, 146-2, a bandpass filter 147 and amplifier 148. As will be understood shortly, the signal radiated by the transmitter 100 in this embodiment has a continuous phase and employs Quadrature Phase Shift Keyed (QPSK) modulation in order to communicate information to the receiver 150.

The input OC-3 formatted optical signal is first fed to the optical to voltage transducer 112. The transducer 112 produces at its output a raw transport bitstream. For an input optical signal of the OC-3 format, the transport bit stream is a digital signal at a 155.52 Mbps rate. The raw transport bit stream is then fed to a lowpass filter 114 to remove any artifacts of the optical to voltage conversion process. It should be understood that other digital input signal types may be supported, such as OC-1, OC-12 or other optical range transport signals.

After being converted to a voltage from the optical carrier, the input baseband signal is directly fed to the control inputs of the data formatter 141. For QPSK operation, the data formatter 141 drives the phase modulator 116 only. The phase modulator 116 provides a phase-deviated microwave carrier at its output, which shifts in phase according to the logic state of the input transport signal.

The frequency of the local oscillator 144 portion of the direct phase modulator 116 is determined by the multiplication factor implemented by the following multiplier 118, and optional multiplier 126. For example, given an OC-3 input signal and a desired output signal in the range of 48-52 GHz, the carrier signal output by the modulator 116 may be in the range of from 10-13 GHz. The oscillators used in the VCO 144 are therefore not particularly narrow band or stable at such high operating ranges in the 40 GHz and above range. Thus, the approach here is to use a more stable VCO 144 source at a lower range, such as in the 10-13 GHz range, and then to rely upon the multiplier 118 and/or 126 to shift the VCO output up to the desired operating band.

The first-stage bandpass filter 120 removes artifacts of the direct modulation process. Unlike heterodyne receivers, no sidebands are created. Artifacts of the direct modulation process occur only at multiples of the VCO 144 carrier and not at image frequencies and no RF sidebands are generated. Thus, the first-stage bandpass filter 120 need only remove the 10-13 GHz range harmonics on either side of the output 50 GHz range carrier frequency. It therefore need not be a particularly sharp roll off filter.

A medium range buffer amplifier 122 then receives the filtered signal and forwards it to an output waveguide filter 130.

The waveguide filter 130 further reduces the harmonics of the VCO 144. It need not be an image-reject filter. Such image-reject filters, if they were needed, would further increase the cost. Elimination of the heterodyne stages, while not providing as bandwidth efficient an approach, does produce a less expensive radio.

As can now be appreciated, this approach implements direct digital modulation using a sub-phase deviation approach. In particular, the output signal is generated by first using a stable voltage controlled oscillator to produce a signal in a band that is a sub-multiple of the ultimately desired output microwave frequency carrier. The VCO output signal is then subjected to a phase modulator that deviates the phase by a desired phase amount that has been divided by a particular factor. This same particular factor is then used by an output frequency multiplier to multiply the resulting phase modulated microwave signal to the desired higher output carrier frequency. The phase deviation of the modulator is thus chosen to be the reciprocal of the multiplication factor implemented by the frequency multiplier.

For example, if the frequency multiplication factor of 4 is to be applied to the output of the VCO, and the QPSK implementation is to ultimately provide output signals at phases of 0, 90, 180, and 270 degrees, the input phase modulator implements phase shifts of 0, 22.5, 45, and 67.5 degrees, respectively.

In a case where a multiplication factor of 8 is introduced in the output signal processing chain, the phase deviation is one-eighth of the ultimately desired amount. Thus, in such an instance, when, for example, an output carrier signal of 80 GHz is generated from a 10 GHz range of VCO, the sub-angle phase deviation implemented by the phase modulator 116 is in steps of 0, 11.25, 22.5, and 33.75, respectively.

It should also be noted that the amplifiers operate in a saturation mode, which is a significant advantage of the present invention. Specifically, by operating in this mode and using direct modulation, the amplifiers do not need linearity requirements that would otherwise be required if heterodyne approaches that are used in the prior art were used. Because the amplifiers need not operate in their linear region, temperature compensation requirements are relaxed and higher power operation is easier to achieve with simpler circuits. In our experience with the prior art, when heterodyne modulation techniques are used that require linear amplifiers, temperature, temperature compensation schemes utilizing Programmable Read Only Memories (PROM) to adjust amplifier outputs levels were generally required at the indicated output frequency ranges of 40 to 80 GHz.

Another embodiment of the present invention that may be used to generate a Quadrature Amplitude Modulated (QAM) output signal via post multiplication phase modulation is shown in Fig. 7. The QAM implementation represents a generalization of the PSK case of Fig. 6, as QAM provides a way for the amplitude of the transmitted signal to also communicate information as well as the phase.

As seen in Fig. 7, this configuration receives the input optical signal 110 and feeds it to an optical to voltage transducer 112, filter 114, and data formatting integrated circuit 140 as for the QPSK embodiment described above. However, with this implementation, the phase modulation technique is somewhat different. Rather than phase-modulate the carrier before multiplication, phase and optional amplitude modulation are introduced after carrier multiplication.

More specifically, a carrier signal is generated by a local oscillator 144 that feeds a multiplier 118, a band-pass filter 120, a buffer amplifier 122, and an output waveguide filter 130 as in the previously described embodiments. Optionally, as before, a second stage band-pass filter 124 and multiplier 126 may be utilized to achieve 80 GHz operation.

The phase modulation is provided post-multiplication by feeding the data bits output by the formatter 140 to a Digital to Analog (D/A) converter 192 and a pair of PIN diodes 194 and 195. The generated microwave carrier signal is then fed from the waveguide filter 130 to a PIN attenuator 143 which in turn feeds a pair of circulators 196 and 197. The purpose of the PIN attenuator 143 is to provide the amplitude modulation portion of a QAM signal at the output. The signal output from the circulator 197 is then fed to the antenna 132.

The combination of the PIN diodes 194 and 195 and circulators 196 and 197 implement one of four different phase shifts, as controlled by the least significant data bits 191-1 and 191-2 output by the formatter 140. These two least significant data bits are fed to a respective one of the PIN diodes 194 and 195. They implement a 0 or 90 degree phase shift, in the case of the PIN diodes 194, and a 0 or 180 degree phase shift, in the case of PIN diodes 195. Thus, it can be considered that a first one of the PIN diodes implements a first phase shift, P1, and a second implements a second phase shift, P2. The PIN diodes 194 and 195 reflect the input signal into either of two phases, e.g., into either one of two signal paths, and the reflected signal is then fed out to the respective one of the circulators 196 and 197.

The data formatting integrated circuit 140 provides data outputs 191 that represent encoded data bits. In the illustrated embodiment, this may be a total of as many as four different data bits represented by 16 different states of the modulated carrier. In the case where four data bits are selected, then the implementation provides for sixteen level QAM signaling at the output. The two most significant bits are used to determine a modulated signal amplitude. The two least significant bits a modulated signal phase as for the QPSK case.

The D/A converter 192 may thus include a digital to analog conversion process for generating an analog voltage from the two most significant data bits 191-3 and 191-4. The voltage output from this D/A converter 192 drives the PIN attenuator 143. The PIN attenuator 143 attenuates the signal amplitude output from the waveguide filter 130 by a desired amount as indicated by the data bits 191.

In Fig. 8, an exemplary receiver 150 for the PSK signals generated by the circuit of Figs. 6 or 7 is described in detail. The receiver 150 includes a receive antenna 151, an input waveguide filter 152, a low-noise amplifier 154, a bandpass filter 156, a local reference generator 160, a phase demodulator 161, a pair of lowpass filters 163-1, 163-2, a pair of buffer amplifiers 162-1, 162-2, a pair of analog to digital (AD) converters 186-1, 186-2, a data formatting integrated circuit 189, and a voltage to optical transducer 170.

The input signal provided by the receiver antenna 151 is fed to the waveguide filter 152. This filter 152, having a center frequency in the 50 or 85 GHz range as the case may be, filters the desired signal from the surrounding background signals.

The low-noise amplifier 154 may be implemented as a Monolithic Microwave Integrated Circuit (MMIC) feeding a planar bandpass filter 156 in the 50 or 85 GHz range. The low-noise amplifier 154 typically has a 6-8 decibel (dB) noise figure providing 10-20 decibels of gain.

The local oscillator reference generator 160 consists of a 10-13 GHz oscillator 157, frequency multiplier 158, and bandpass filter 159. These components are identical to the corresponding components in the PSK transmitter. Note here that the multiplication factor 158 may be implemented by one or more individual frequency multipliers although only a single block is shown in the diagram.

The phase demodulator 161 includes a pair of image reject mixers 172-1 and 172-2 offset in quadrature by the phase shifter 174. As is well known in the art, the heterodyning of a local reference signal as generated by the reference oscillator 160 when mixed against the incoming signal from the antenna 151 will produce an in-phase (I) and quadrature (Q) versions of the input signal.

The lowpass filters 163-1 and 163-2 provide the baseband information to a pair of respective buffer amplifiers 162-1, 162-2. Thus the resulting signal is the basic 55.52 MHz information that was phase modulated onto the microwave frequency carrier. In a case where the information is coded as QPSK, each signal output by the buffer amplifier may actually represent two different bits. The respective A/D converters 186-1 and 186-2 thus perform the required two-bit conversion. The data formatting IC 189 then reformats this data to be fed to the optical to voltage transducer 170.

The oscillator 157 may receive an error correction signal from the data formatting IC. In such an instance, a phase locked oscillator 157 is provided, in a manner which is well known in the art.

Different implementations of QAM modulation would require different implementations of A/D converters 186. For example, if binary phase shift keying (BPSK) is implemented the A/D converters 186 require only a single bit conversion; if however, if 8 level QAM is implemented by such for example the circuit of Fig. 3, then three bit A/D converters would be necessary. Likewise, if the level QAM is used, the A/D converts should have at least 4 bit accuracy.

It should be understood that various alternate arrangements of the two described embodiments are possible. For example, in the sub-phase deviation embodiment of Fig. 6, there may be introduced attenuators at one or more places in the signal chain in order to accommodate QAM type modulation. For example, an attenuator might be implemented at the output of amplifier 148 prior to multiplication by multiplier 118.

In a similar vein, the embodiment of Fig. 7 may be utilized to generate a QPSK modulated signal through the elimination of the pin attenuator 143 and using the data formatter 140 to simply drive the circulators 196 and 197.

The present invention also enjoys an advantage in the receiver design in that variable data rate modulated signals may be easily accommodated. In particular, by avoiding the use of heterodyning schemes, an asynchronous detection scheme is possible. This is important in that it also tends to reduce the cost of an entire system.

The invention thus provides for direct modulation of the input bitstream utilizing Continuous Phase Shift Keying. No manipulation of the bitstream is required such as in the case of baseband to heterodyne conversion approaches. Furthermore, because of the direct up-conversion to the desired microwave frequency carrier, multiple heterodyne stages are eliminated. Heterodyne stages, while providing for efficient filtering topologies, have been found to create interference and spurious noise problems and typically require temperature compensation at microwave operating frequencies.

By directly modulating the carrier source, such as provided by a voltage-control oscillator at a phase deviation less than the desired ultimate deviation rate by a factor of 1/n, with n being the multiplication factor in the up-conversion chain, the overall design is greatly simplified. Standard microwave component building blocks can be used in a highly-producible assembly as a result.

While this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the scope of the invention encompassed by the appended claims.

CLAIMS

What is claimed is:

1. A transport to microwave radio frequency adapter that accepts an input telecommunications transport signal on an input port and converts information in such signal to a desired microwave Radio Frequency (RF) carrier, the input transport signal carrying information at an input bit rate, the apparatus comprising:

a direct modulator, coupled to receive the transport signal and to modulate the output of the local reference oscillator in response thereto;

a local reference oscillator, connected to provide a first microwave carrier; and

a frequency multiplier, connected to receive the modulated output of the local reference oscillator and to multiply the output thereof to a desired microwave RF carrier frequency.

2. An apparatus as in claim 1 wherein the direct modulator comprises:

a voltage-control oscillator, coupled to receive the transport signal, the voltage-control oscillator implementing a continuous phase Frequency Shift Keyed (FSK) deviation such that a first frequency is selected to indicate a first logical value for an input data bit in the transport signal and a second frequency is selected to indicate a second logical value for an input data bit in the transport signal, the deviation between the two frequencies selected to be equal to a predetermined fraction of the input bit rate; and

a frequency multiplier connected to receive the output of the voltage-controlled oscillator and to multiply the output of the voltage controlled oscillator to the desired microwave RF carrier.

3. An apparatus as in claim 1 wherein the telecommunications transport signal is provided on an optical physical medium.

4. An apparatus as in claim 3 additionally comprising:

an optical-to-voltage transducer connected to receive the telecommunications signal and to provide a baseband electrical signal at an output.

5. An apparatus as in claim 2 wherein the frequency multiplier implements a multiplication factor which is a reciprocal of the predetermined fraction used as the deviation in the voltage-controlled oscillator.

6. An apparatus as in claim 5 wherein the frequency multiplier is implemented in a plurality of frequency multiplication stages.

7. An apparatus as in claim 1 wherein the voltage-controlled oscillator and frequency multiplier perform a direct conversion of the input transport signal to the microwave RF carrier.

8. An apparatus as in claim 7 wherein the direct conversion is performed without using the input transport signal to modulate an intermediate carrier signal.

9. An apparatus as in claim 1 additionally comprising:

a microwave bandpass filter connected to the output of the frequency multiplier to filter harmonics of the carrier frequency of the voltage-controlled oscillator.

10. An apparatus as in claim 1 additionally comprising:

a microwave RF to transport adapter, to convert a received microwave RF signal to a transport signal carrying an output telecommunications transport signal.

11. An apparatus as in claim 10 wherein the microwave RF to transport adapter further comprises:

an oscillator, operating at a carrier frequency which is a predetermined fraction of a desired direct down-conversion frequency;

a frequency multiplier, connected to receive the oscillator output, and to multiply the oscillator output up to the desired direct down-conversion frequency; and

a mixer, coupled to the frequency multiplier and the microwave RF signal, to provide a down-converted transport signal.

12. An apparatus as in claim 11 additionally comprising:

a pair of bandpass filters, a first bandpass filter tuned to a frequency which is equal to the down-conversion frequency plus one-half a data rate of the down-converted transport signal, and a second bandpass filter tuned to a frequency which is equal to the down-conversion frequency minus one-half the data rate of the down-converted transport signal.

13. An apparatus as in claim 12 additionally comprising:

a pair of detector diodes, each diode connected to a respective one of the bandpass filters, and to each provide a detected signal.

14. An apparatus as in claim 13 additionally comprising;

a differential amplifier, connected to receive the two detected signals, and to provide the output transport signal.

15. An apparatus as in claim 14 additionally comprising:

an electrical-to-optical transducer, coupled to the differential amplifier output, to provide an optical transport signal.

16. An apparatus as in claim 1 wherein the direct modulator comprises:

a switch implementing an On-Off Keyed (OOK) modulation such that the on-state is selected to indicate a first logical value for an input data bit in the transport signal and the off-state is selected to indicate a second logical value for an input data bit in the transport signal, the switch rate selected to be equal to the input bit rate.

17. An apparatus as in claim 16 wherein the oscillator, switch and frequency multiplier perform a direct conversion of the input transport signal to the microwave RF carrier.

18. An apparatus as in claim 17 wherein the direct conversion is performed without using the input transport signal to modulate an intermediate carrier signal.

19. An apparatus as in claim 11 additionally comprising:

a bandpass filter, tuned to a frequency which is equal to the down-conversion frequency.

20. An apparatus as in claim 19 additionally comprising:

a detector diode, connected to the bandpass filter, and to it provide a detected signal.

21. An apparatus as in claim 20 additionally comprising;

an amplifier, connected to receive the detected signal, and to provide the output transport signal.

22. An apparatus as in claim 21 additionally comprising:

an electrical-to-optical transducer, coupled to the amplifier output, to provide an optical transport signal.

23. An apparatus as in claim 1 wherein the direct modulator comprises:

a phase encoder, coupled to receive the transport signal, the phase encoder implementing a Phase Shift Keyed (PSK) encoding such that at least first phase is selected to indicate a first logical value for an input data bit in the transport signal and a second phase is selected to indicate a second logical value for an input data bit in the transport signal, the deviation between the two phases selected to be equal to a predetermined value.

24. An apparatus as in claim 23 additionally comprising:

a phase modulator, connected to impart a direct phase modulation to the microwave RF carrier.

25. An apparatus as in claim 23 wherein the direct modulator and frequency multiplier perform a direct phase conversion of the input transport signal to the microwave RF carrier.

26. An apparatus as in claim 25 wherein the direct phase conversion is performed without using the input transport signal to modulate an intermediate carrier signal.

27. An apparatus as in claim 23 wherein the phase modulator implements a sub-phase deviation phase shift prior to the frequency multiplier.

28. An apparatus as in claim 27 wherein the sub-phase deviation phase shift is equal to an output desired phase shift divided by a frequency multiplier factor implemented by the frequency multiplier.

29. An apparatus as in claim 23 wherein the phase modulator implements a phase deviation after the frequency multiplier.

30. An apparatus as in claim 29 wherein the phase modulator imports a direct phase shift to the microwave RF carrier.

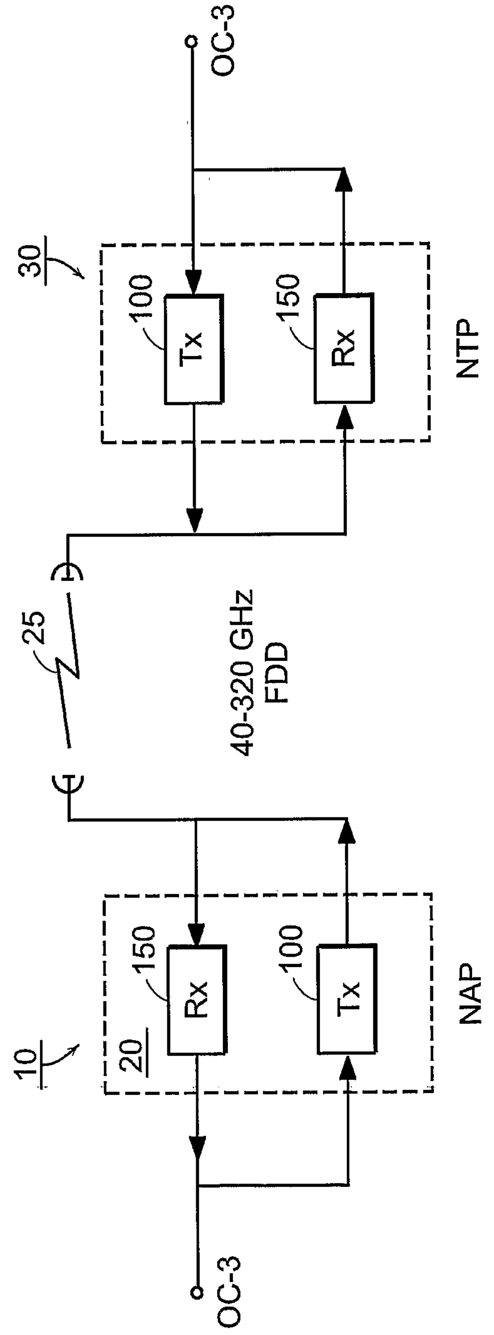

OC-3
10
20
150
Rx
100
Tx
NAP
25
40-320 GHz
FDD
30
100
Tx
150
Rx
NTP
OC-3

FIG. 1

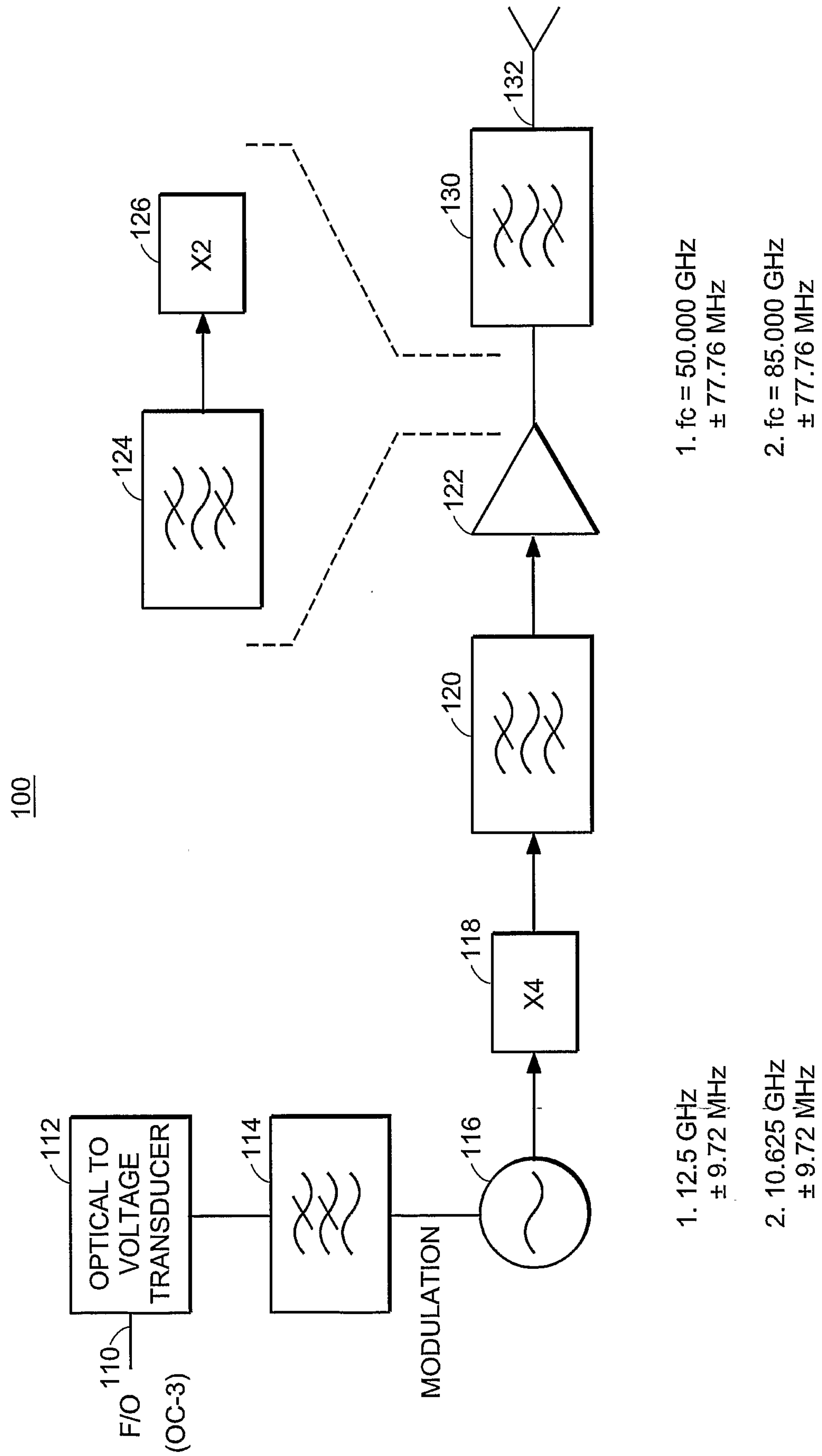

100
F/O
(OC-3)
110
112
OPTICAL TO VOLTAGE TRANSDUCER
114
MODULATION
116
118
X4
120
122
124
126
X2
130
132
1. 12.5 GHz ± 9.72 MHz
2. 10.625 GHz ± 9.72 MHz
1. fc = 50.000 GHz ± 77.76 MHz
2. fc = 85.000 GHz ± 77.76 MHz

FIG. 2

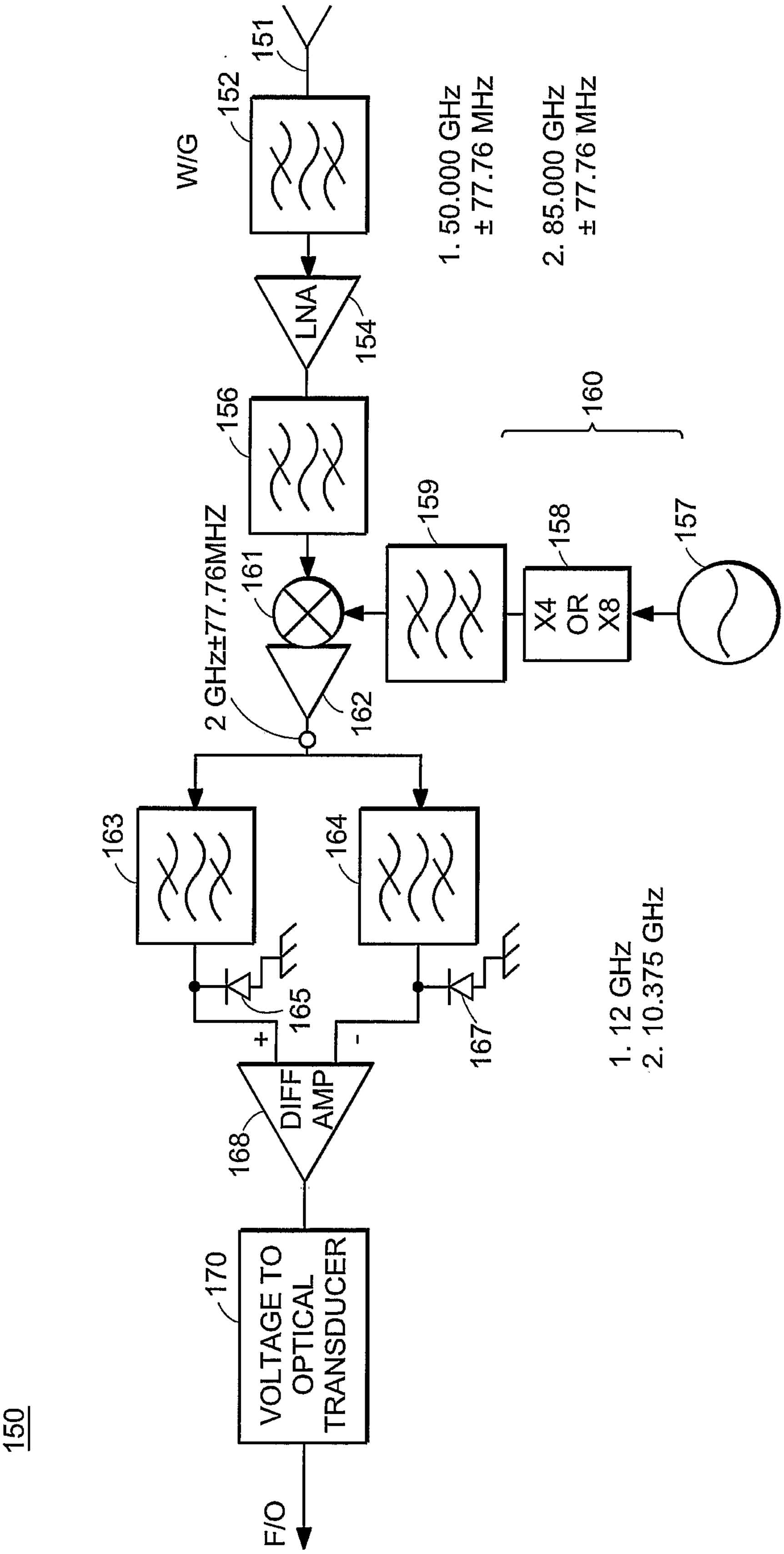

151
152
W/G
1. 50.000 GHz
±77.76 MHz
2. 85.000 GHz
±77.76 MHz
LNA
154
156
160
159
158
X4
OR
X8
157
161
2 GHz±77.76MHZ
162
163
164
165
167
1. 12 GHz
2. 10.375 GHz
+
-
DIFF
AMP
168
170
VOLTAGE TO
OPTICAL
TRANSDUCER
150
F/O

FIG. 3

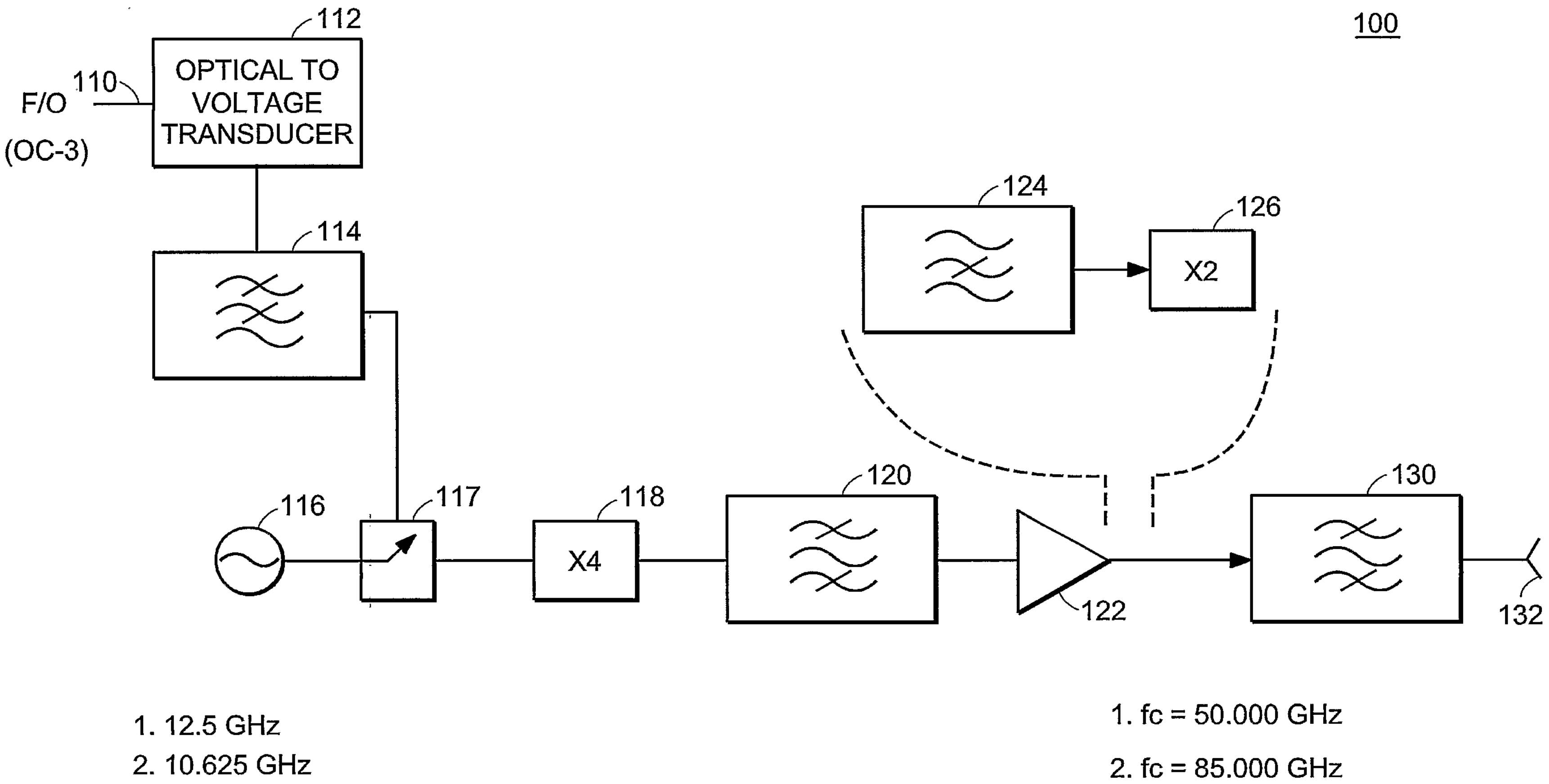

100
F/O
(OC-3)
110
112
OPTICAL TO VOLTAGE TRANSDUCER
114
116
117
118
X4
120
122
124
126
X2
130
132
1. 12.5 GHz
2. 10.625 GHz
1. fc = 50.000 GHz
2. fc = 85.000 GHz

FIG. 4

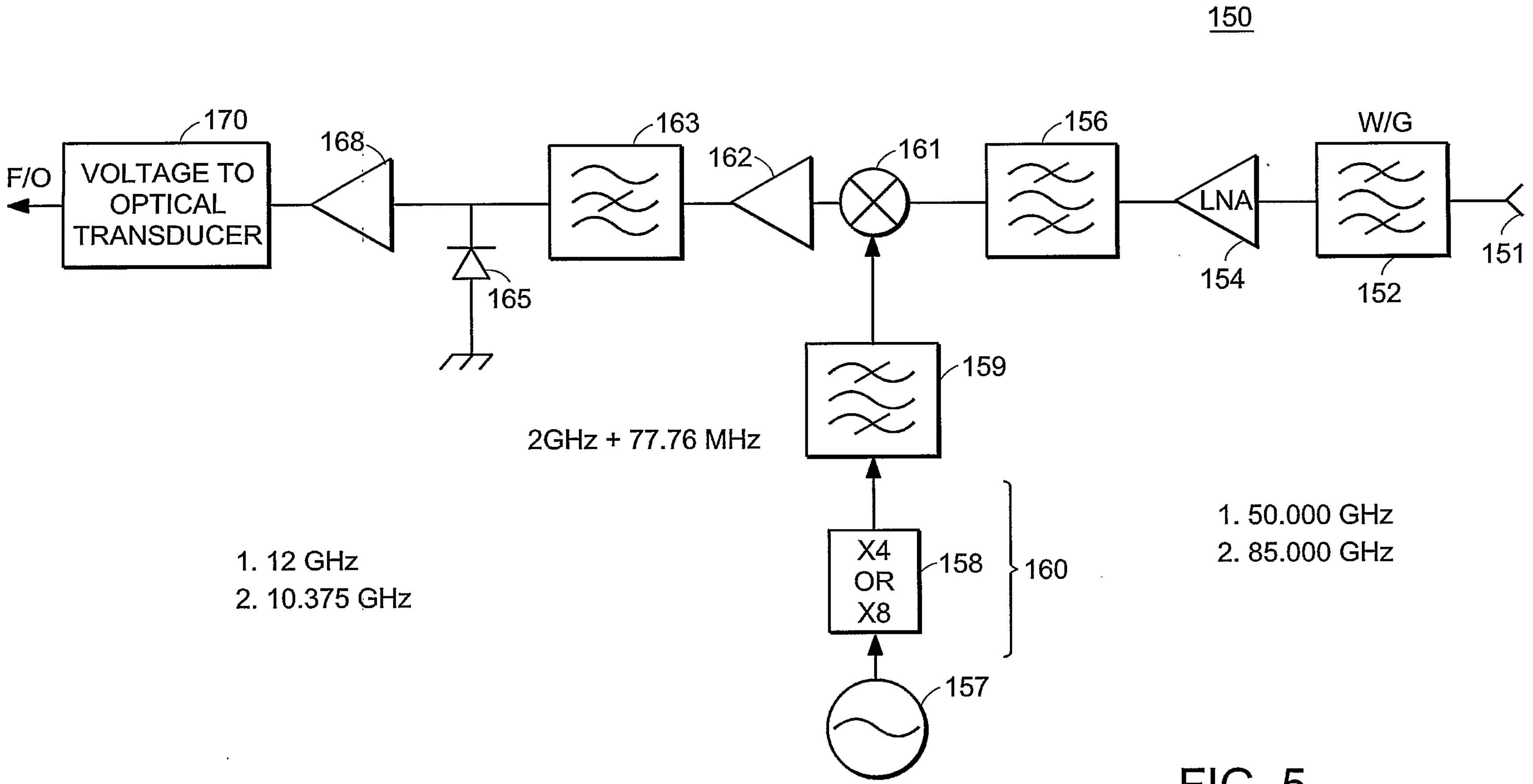
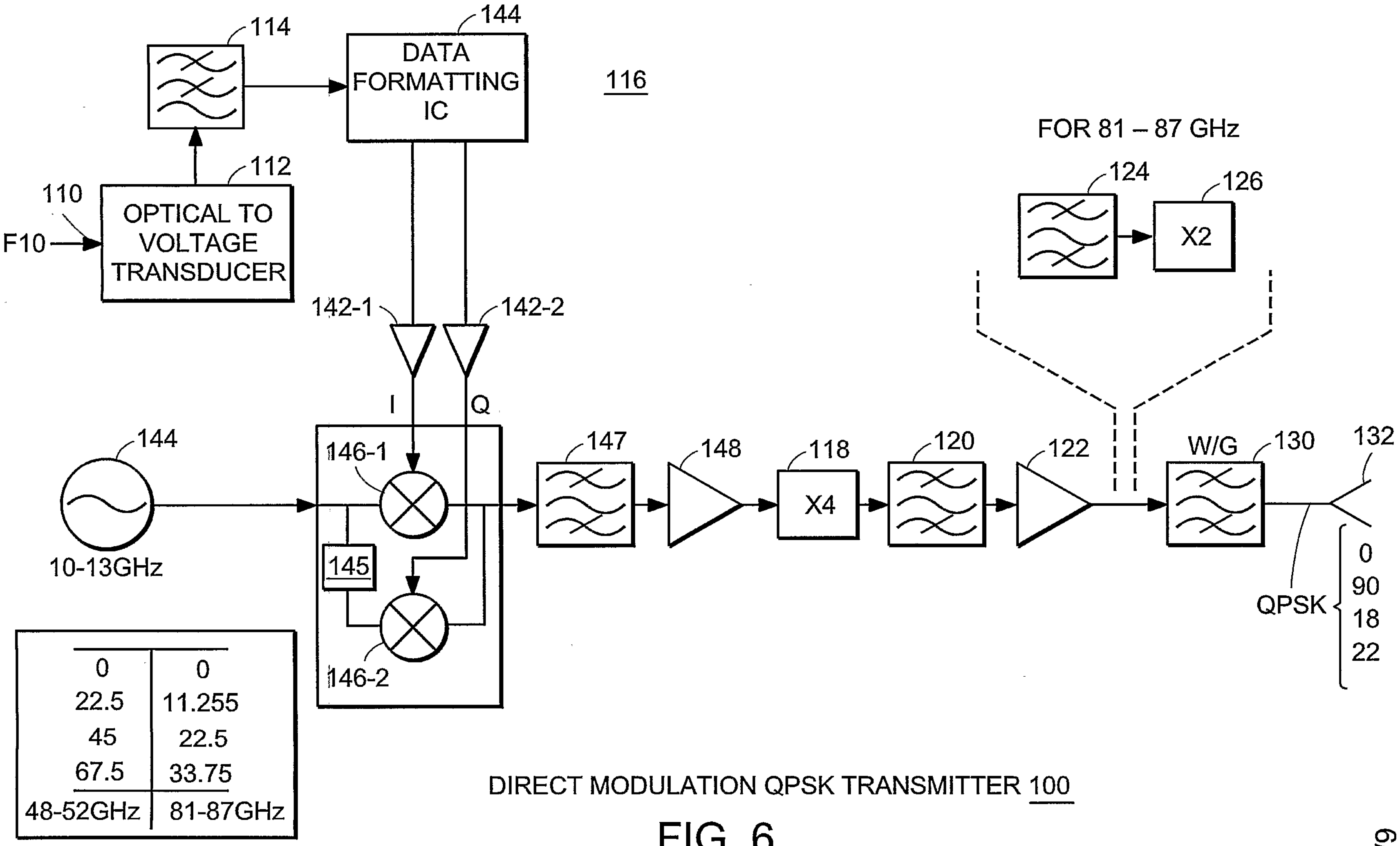

150
W/G
151
152
LNA
154
156
161
162
163
165
168
170
VOLTAGE TO OPTICAL TRANSDUCER
F/O
159
2GHz + 77.76 MHz
X4 OR X8
158
160
157
1. 50.000 GHz
2. 85.000 GHz
1. 12 GHz
2. 10.375 GHz

FIG. 5



DIRECT MODULATION QPSK TRANSMITTER 100

FIG. 6

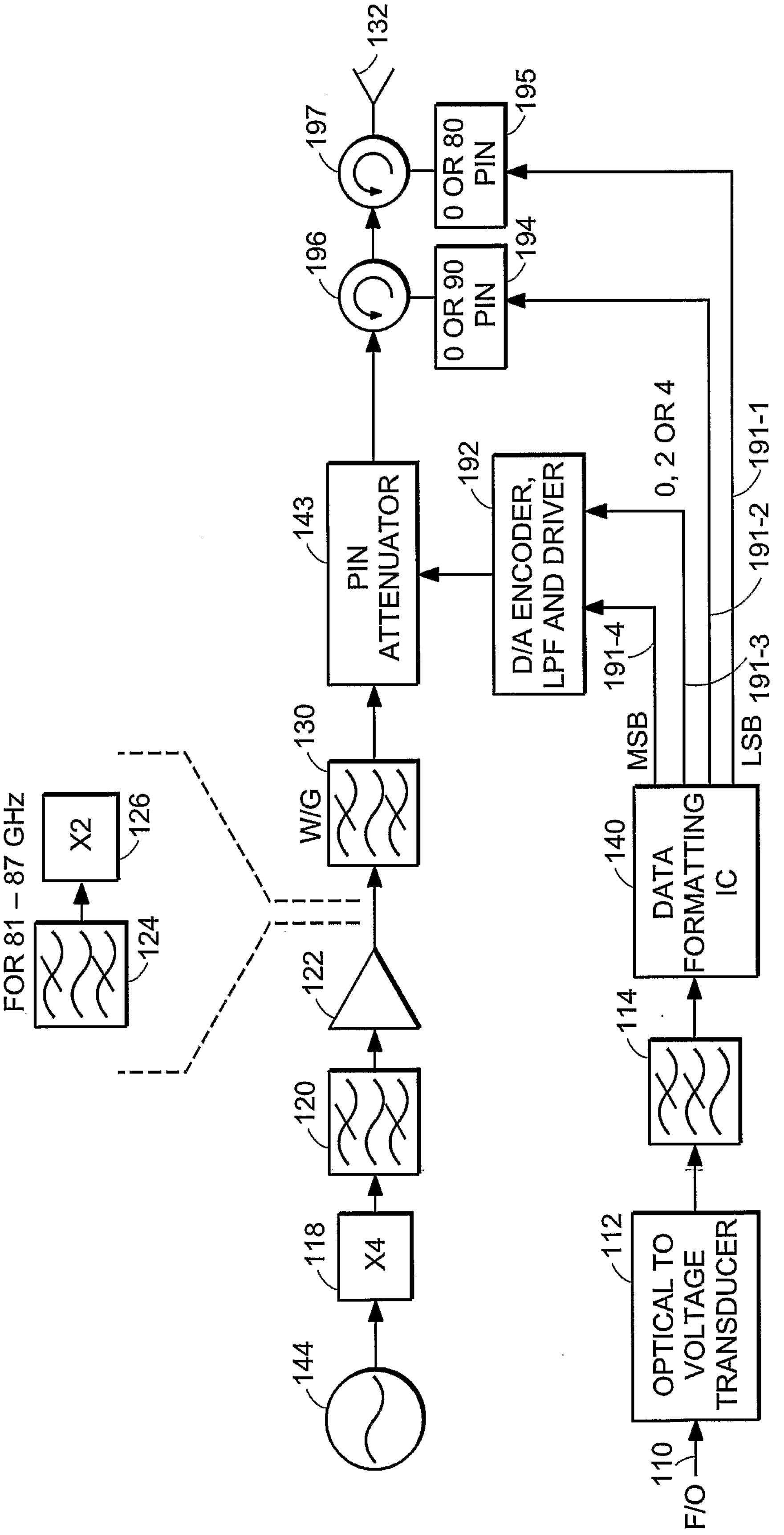
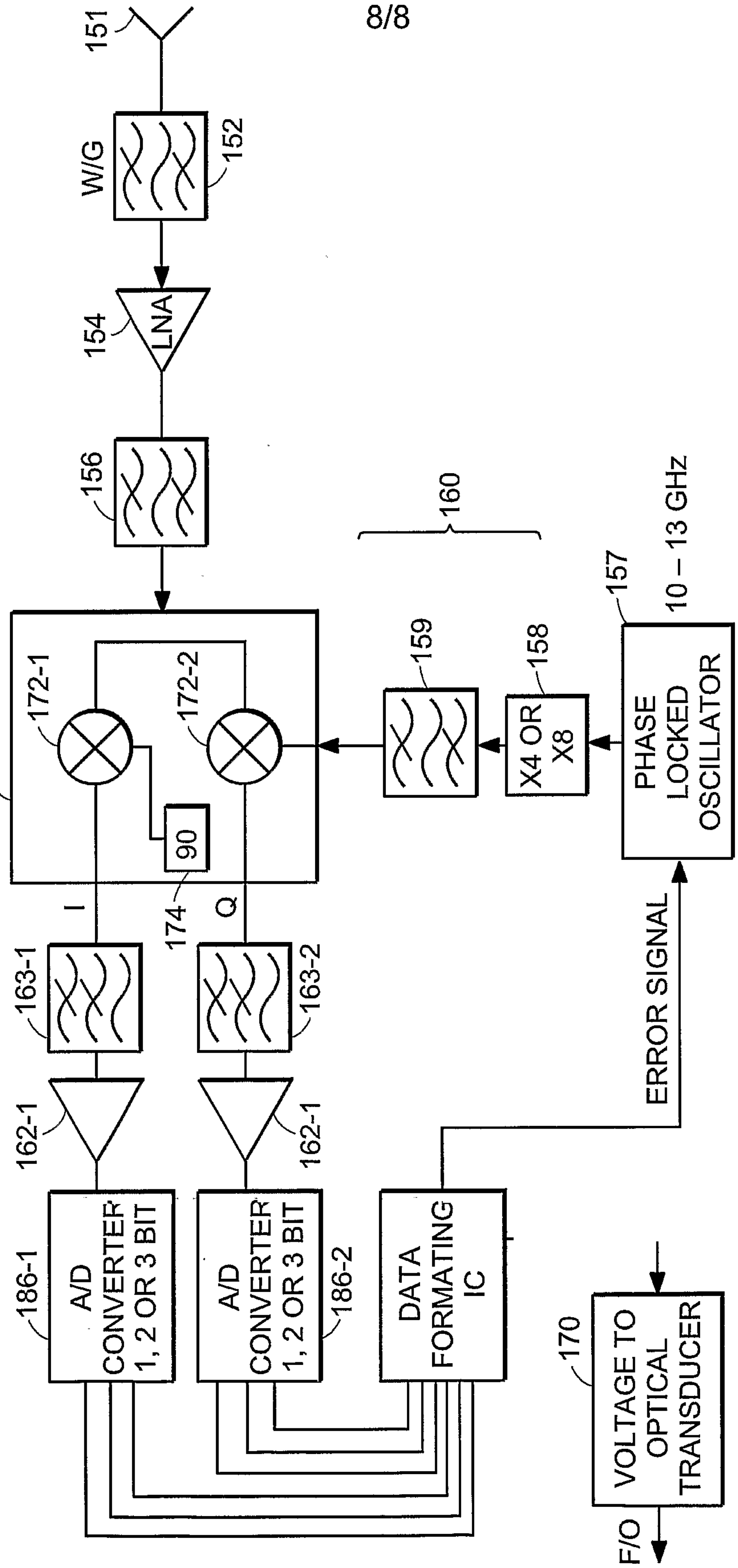


FIG. 7

TECHNIQUE FOR DIRECT MODULATION



DIRECT MODULATION QPSK/QAM RECEIVER 150

FIG. 8

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US02/07412

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : *H04J 3/00; H04M 11/00*
US CL : 375/220, 272; 341/13
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 375/220, 272, 295, 303, 306, 308; 332/100, 103, 117, 119; 341/13; 455/118.

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

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,995,812 A (SOLEIMANI et al.) 30 November 1999 (30.11.1999), figure 2 and column 3, line 55 to column 4, line 57.	1
X, P	US 6,353,735 B1 (SORRELLS et al.) 05 March 2002 (05.03.2002), figures 14 and 50, column 1, line 53 to column 2, line 12.	1
X, P --- Y, P	US 6,366,620 B1 (JACKSON et al.) 02 April 2002 (02.04.2002), figure 3 and column 5, line 45 to column 6, line 50	1, 2, 7, 9 ----------- 3, 4
X --- Y	US 5,809,395 A (HAMILTON-PIERCY et al.) 15 September 1998 (15.09.1998), figure 4 and column 16, line 29 to column 17, line 47.	1 ----------- 3, 4
X --- Y	US 5,706,310 A (WANG et al.) 06 January.1998 (06.01.1998), column 1, line 13 to column 2, line 32	1 ----------- 23 - 29

☒ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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

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

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

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

“&” document member of the same patent family

Date of the actual completion of the international search 21 June 2002 (21.06.2002)	Date of mailing of the international search report 19 JUL 2002
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703)305-3230	Authorized officer Dung X. Nguyen Telephone No. (703) 305-4892

Form PCT/ISA/210 (second sheet) (July 1998)

INTERNATIONAL SEARCH REPORT

International application No. PCT/US02/07412

C. (Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 5,903,609 A (KOOL et al.) 11 May 1999 (11.05.1999), figures 1 and 2, column 3, line 55 to column 5, line 44	1,2, 7, 9, 23 - 29 ---------- 3, 4
Y	US 6,282,180 B1 (PANETH et al.) 28 August 2001 (28.08.2001), figure 2 and colum 1, line 26 to column 2, line 38.	23 - 29
Y	US 6,222,658 B1 (DISHMAN et al.) 24 April 2001 (24.04.2001), figure 3 and column 7, lines 1 - 67.	3, 4, 16 - 22