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(54) **Title**: NOISE DETECTION, DIAGNOSTICS, AND CONTROL OF MODE-LOCKED LASERS

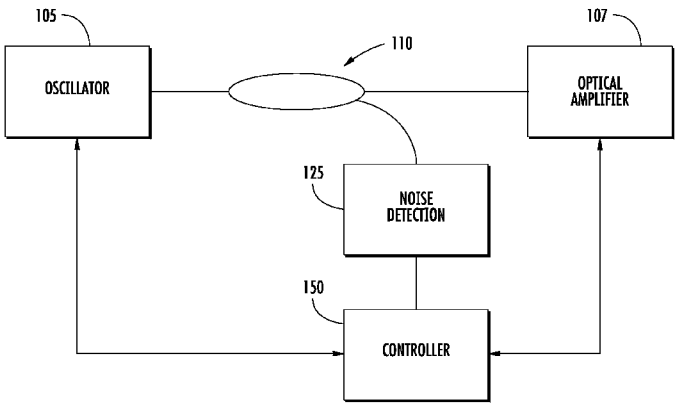


FIG. 1

(57) **Abstract**: The present invention features a laser based system configured with a noise detection unit. The system includes a mode-locked oscillator. A noise detection unit includes at least one optical detector that monitors optical pulses generated by the mode-locked oscillator and produces an electrical signal in response to the optical pulses. The noise detection unit includes a first filter to transmit signal power over a signal bandwidth which includes the mode-locked laser repetition frequency, frep. The noise detection unit may include one or more filters to transmit power over a noise bandwidth that substantially excludes repetition frequency, frep. Non-linear signal processing equipment is utilized to generate one or more signals representative of the power in the signal bandwidth relative to the power in the noise bandwidth. The system includes a controller operable to generate a signal for controlling the laser based system based on the relative power.

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NOISE DETECTION, DIAGNOSTICS, AND CONTROL OF MODE-LOCKED LASERS

FIELD OF THE INVENTION

[0001] This invention relates generally to noise detection, diagnostics, and control of pulsed laser systems, and more particularly systems in which mode-locked lasers are utilized.

BACKGROUND

[0002] Pulsed laser systems comprising an oscillator and high power fiber amplifier(s) are well known in the art. See, for example, U.S. Pat. Nos. 6,208,458; 6,181,463; and 5,696,782. Conventional systems typically operate at a fixed pulse width and repetition rate. However, systems with variable pulse widths and repetition rates have also been developed. For example, see U.S. Pat. Nos. 6,347,007; 6,335,941; and 6,433,306 to Grubb et al. For certain applications, it is desired that the output pulse energy of these types of systems be maintained at a constant value as the pulse width and repetition rate of the pulse source is varied. This problem is addressed in U.S. Patent 7,505,196 which discloses methods and systems for controlling and protecting pulsed high power fiber amplifier systems.

[0003] The gain of the amplifier system depends on the rate at which energy is stored into, and depleted from, the doped fiber. Therefore, output pulse energy varies as a function of the rate of energy storage into the amplifier and the repetition rate of the seed, which extracts energy from the amplifier. A known method includes adjusting the gain of the amplifier by adjusting the power of the amplifier pump diode by changing its drive current as a function of the seed source pulse energy and repetition rate. A further alternative, which is suitable under

some conditions, includes changing the pulse energy of the seed source by modulating the source directly or attenuating its input to the power amplifier.

[0004] Methods for controlling and protecting amplifiers from undesirable operation modes of modelocked lasers are described in U.S. Patent 7, 505,196, entitled: "Method and apparatus for controlling and protecting pulsed high power fiber amplifier systems", assigned to the assignee of the present invention, and hereby incorporated by reference in its entirety.

[0005] US Patent 6,839,363, entitled "Digital control of actively mode-locked lasers" discloses a processor that digitally extracts noise information from multiple monitor signals generated from the laser output. Control functions are achieved with one or more bandpass filters covering various portions of the frequency range of the laser output. In U.S. Patent 6,839,363, a microprocessor digitally diagnoses the operating condition of the laser based on the noise information. Mode locking may be maintained by reducing the noise. An array of A/D and D/A converters allow for digital control of the active mode-locked laser.

[0006] Takara et al, in "Stabilisation of a modelocked Er-doped fibre laser by suppressing the relaxation oscillation frequency component", Electronic Letters, 16 February 1995, Vol. 31 No. 4, 292-293, disclosed a stabilizing method based on the observation that the relaxation oscillation RF power of the detected output pulses is a good measure of instability. Stable bit-error-free operation at 6.3 GHz for long periods was reported. The bandwidth of the optical receiver was set in the range from 10Hz to 200 kHz. The RF power ratio between the 6.3 GHz mode-locking frequency and background noise exceeded 70dB.

[0007] Mode-locked laser systems are also widely used in frequency metrology, where the mode-locked laser acts as a frequency comb that can be used for precision measurements. Generally, such frequency combs are susceptible to noise. Low noise operation of the mode-locked laser can further improve precision. For example, high sensitivity detection and

elimination of rapid multiple (double) pulsing while providing low latency for high speed execution of control functions is desirable.

[0008] A need exists for high sensitivity diagnostic tools for use with mode-locked lasers, particularly for application to frequency comb metrology. It is desirable to distinguish noisy and quiet operation of mode-locked lasers, and to rapidly detect pulse instabilities such as double pulses, period doubling, Q-switch mode-locking and other phenomena which degrade the quality of mode-locked signals, and which may occur over a wide frequency range.

SUMMARY

[0009] An object of the invention is to monitor noise of a mode-locked laser source over a wide frequency bandwidth and wide dynamic range, and to control operation of a laser based system in which the mode-locked laser is utilized.

[0010] An object of the invention is to protect a high power amplifier from damage caused by gain buildup in excess of the damage threshold of the amplifier.

[0011] An object of the invention is to monitor noise of a mode-locked oscillator and to provide operation of the mode-locked oscillator as a stable frequency comb laser for precision frequency metrology.

[0012] One aspect of the present invention features a laser based system configured with a noise detection unit. The system includes a mode-locked oscillator generating optical pulses at a repetition frequency, f_{rep}. A noise detection unit includes at least one optical detector that monitors optical pulses generated by the mode-locked oscillator and produces an electrical signal in response to the optical pulses. The noise detection unit includes a first filter to transmit signal power over a signal bandwidth which includes repetition frequency, frep. The noise detection unit optionally includes one or more filters to transmit power over a noise bandwidth that substantially excludes repetition frequency, frep. Non-linear signal processing

equipment is utilized to generate one or more signals representative of the power in the signal bandwidth relative to the power in the noise bandwidth. The system includes a controller which estimates the relative power in the signal bandwidth and in the noise bandwidth, and is operable to generate a signal for controlling the laser based system based on the relative power.

[0013] The first filter may include a bandpass filter centered about frep or a bandpass filter centered at any harmonic of frep.

[0014] One or more optional filters may include a low pass filter with a frequency cutoff less than frep.

[0015] A low pass filter may have a cutoff as low as about $f_{rep}/2$.

[0016] Optical pulses may be monitored by extracting a portion of the optical pulses with an optical tap which is coupled to the detector.

[0017] Non-linear signal processing equipment may provide an available dynamic range of at least about 60 dB via signal compression, and may include a logarithmic converter.

[0018] The available dynamic range may be in the range from greater than 80 dB to about 100 dB.

[0019] The controller may include digital signal acquisition and processing equipment, for example high resolution A-D converter(s), to provide for an estimate of the relative power.

[0020] The system may include at least one optical amplifier downstream from the mode-locked oscillator, and the controller may generate a signal to decrease the energy of a pump diode utilized to pump the mode-locked laser and/or the downstream optical amplifier.

[0021] The controller may generate a signal for control of the temperature, pressure, and/or position of an intra-cavity element of the mode-locked oscillator.

[0022] The controller may comprise high-speed digital circuitry to provide one or more signals representative of at least the relative power in a signal bandwidth and a noise

bandwidth. The controller is capable of generating said signals with a low-latency in the range from about several hundred ps to 20 ns.

[0023] The system may include a frequency comb source for optical metrology.

[0024] The system may be configured as a portion of a micromachining system or laser surgery system.

[0025] In at least one embodiment a noise detection unit and controller are provided to monitor the noise of injected pulses into the amplifier system, and to compare the noise to a predetermined maximum noise level, and if higher than this maximum noise level, to disable or reduce the current to the amplifier pump diode to prevent it from being damaged.

[0026] In at least one embodiment the noise of injected oscillator pulses, an external signal, or both is monitored. If the noise exceeds a certain threshold the diode pump current is reduced or shut off.

[0027] In at least one embodiment a noise detection unit and controller includes a means for comparing the amplitude of a pulse being injected into a fiber amplifier with a predetermined minimum amplitude value, and a means to disable or reduce the current to the amplifier pump diode to prevent it from being damaged whenever the amplitude is lower than this predetermined minimum.

[0028] A device in accordance with an embodiment of the invention also provides a means of selecting and attenuating the seed pulses such that the amplified output pulses are of uniform energy.

BRIEF DESCRIPTION OF THE DRAWINGS

[0029] Objects and features of the present invention will become more readily apparent from the following detailed description of the preferred embodiments taken in conjunction with the

accompanying drawings:

[0030] FIG. 1 schematically illustrates an arrangement utilizing a laser source and noise detection arrangement according to an embodiment of the present invention.

[0031] FIGS. 2A-2C are plots illustrating an optical frequency comb and RF spectra of mode- locked lasers:

[0032] FIG. 2A illustrates an optical spectrum of a frequency comb laser.

[0033] FIG. 2B is a plot showing a portion of the RF spectrum of a mode locked laser, which includes the repetition frequency, f_{rep}, and the second harmonic, $2f_{rep}$.

[0034] FIG. 2C is a plot illustrating bandpass and low-pass filtering of the RF spectrum in accordance with an embodiment.

[0035] FIG. 3 schematically illustrates a noise detection system in accordance with an embodiment.

[0036] FIGS. 4a-1-4d-2 are examples comparing exemplary temporal shapes and spectra of mode-locked lasers under (a) low noise conditions and (b) in the presence of noise generated by multiple pulses, unwanted q-switching, and/or random signal fluctuations.

[0037] FIG. 5 schematically illustrates an exemplary fiber-based laser system adapted with a noise detection unit according to an embodiment of the present invention.

[0038] FIG. 6 schematically illustrates an exemplary frequency comb source adapted with a noise detection unit according to an embodiment of the present invention.

DETAILED DESCRIPTION

[0039] A block diagram of a system of the present invention is shown in FIG. 1. This example includes a mode-locked oscillator 105, an optical amplifier 107, a noise detection system 125, and a controller 150. In this arrangement the controller 150 is configured to control and monitor various parameters of both the oscillator 105 and amplifier 107. Exemplary mode-locked oscillators, amplifiers or frequency combs were for example

described in U.S. Patents: 8,031,396 ('396) entitled "Modular, high energy, widely-tunable ultrafast fiber source": 7,649,915 (915), entitled "Pulsed laser sources": 7,809,222 ('222), entitled "Laser-based frequency standards and their applications"; and U.S. Patent Appl. No. 12/955,759 ('759), entitled "Frequency comb system with large comb spacing". The '396, '915, '222 patents, and the '759 application, are hereby incorporated by reference in their entirety.

[0040] In certain embodiments the oscillator output is directed to an amplifier. Preferably, fiber oscillators and amplifiers are used, but solid-state laser oscillators and amplifiers or hybrid systems comprising fiber and solid-state components can also be used. In some embodiments an amplifier 107 may not be required if the pulse energy produced by the oscillator is sufficiently high.

[0041] Oscillator noise may be monitored by directing a fraction of the oscillator output to a noise detection system. A fiber tap, beam splitter, or other suitable beam sampling element 110 may be utilized. One or more outputs of the noise detection system 125 are further processed by a controller 150 which may provide signals for control of the pump laser(s) for the oscillator or amplifier. For example, the controller 150 can turn the amplifier 107 off for protection if elevated noise is detected and/or the pump to the oscillator 105 can be modified in order to return the oscillator into a low noise operational state. The controller 150 may provide signals to modify the cavity length, adjust temperature of intra-cavity optical elements, or other control functions to achieve a desired condition of operation as discussed in the '915 and '222 patents cited above.

[0042] As is well known in the state of the art, the RF spectrum associated with a mode-locked laser comprises a comb of individual RF frequencies separated by the repetition frequency f_{rep} of the oscillator, as indicated. Fig 2a illustrates an optical frequency spectrum 250 of a conventional frequency comb laser. To first order the frequency spectrum is

determined by f_{rep} and f_0. The frequency comb is derived from a mode-locked laser and f_{rep} corresponds to the repetition rate of the pulses generated with the mode-locked laser, whereas f_0 corresponds to the carrier envelope offset frequency. In frequency comb systems a high speed photo detector may be used to measure f_{rep}, whereas f_o may be determined, for example, using an f-2f interferometer, as well known in the state of the art. Because noise sources associated with the mode-locked laser can limit the performance of frequency comb based optical metrology systems it is desirable to maximize the signal to noise ratio in the RF regime.

[0043] Fig 2b illustrates the two first mode-locked frequencies f_{rep} (260-a) and $2f_{rep}$ (260-b) in the RF domain. The RF spectrum may also contain a low amplitude noise continuum 270-a, 270-b broadly spread across the RF spectrum arising from laser amplitude and phase noise. Noise contributions may arise from laser shot noise, diode laser noise, persistent relaxation oscillations, amplitude and/or phase instabilities, unwanted q-switching, double (multiple) pulsing or period doubling etc. Generally, the noise spectrum may be characterized as having noise components which are largely frequency independent, and other frequency dependent components, including narrowband noise components.

[0044] An operational state of a mode-locked laser is desired in which the RF noise in the RF spectrum is minimized. Once a mode-locked laser is operating properly, the energy ratio between the energy contained in the RF comb lines and the noise continuum is effectively maximized. In various embodiments proper mode-locked operation of the laser can be verified by measuring the RF power contained in the RF combs and comparing the measured power with that of the noise continuum.

[0045] A noise detection system is further illustrated in Fig. 3. An extracted portion of the oscillator output is detected with an optical detector 305. The detector arrangement may include an RF amplifier stage (not shown) or other suitable amplifier to convert detector

current to an input voltage. In some embodiments additional detectors/amplifiers arrangements may be utilized to generate voltage and/or current signals for downstream processing and analysis. For example, extraction of the detector DC photocurrent may be used for additional calibration or control functions. The DC photocurrent can be extracted by a bias-T and then detected as a voltage drop over a sense-resistor (not shown), as is well known in the art. Moreover, the detection system may include additional components for analog and/or digital processing and signal conditioning.

[0046] The RF signal generated by converting the optical signal from the oscillator 105 to an electrical signal in the detector 305 is split into multiple parts by an RF power splitter or an RF directional coupler. The splitting ratio does not need to be equal. The RF signal in the first arm is then filtered with low pass filter 310 in order to detect the noise continuum power. Preferably, the low pass filter has a cut-off frequency $f_{cut\text{-}off} < f_{rep}$ with $f_{cut\text{-}off} < f_{rep}/2$ being found as suitable. However, one could just as well detect the noise continuum between f_{rep} and $2f_{rep}$, or a suitable fraction of the range.

[0047] The RF signal in the second arm is then filtered by an RF bandpass filter 320 centered about f_{rep}, and/or $2f_{rep}$ or $3f_{rep}$ etc.

[0048] Those skilled in the art will recognize that the filter characteristics of exemplary low pass filter 310 and bandpass filter 320 may be tailored in various ways for flatness, falloff characteristics, spectral width and the like. In some embodiments a high pass filter may be sufficient provided that noise is negligible relative to power at frep and the harmonics. In some embodiments the upper portion of the spectrum may be filtered or attenuated.

[0049] It is desirable to extend both the measurement speed and sensitivity of noise detection for high repetition rate mode-locked lasers and frequency comb systems. In various embodiments non-linear signal processing equipment is incorporated to provide wide dynamic range operation. Referring to the example of Fig. 3, filtered outputs are received by

a pair of logarithmic amplifiers 330-a, 330-b (e.g.: log converters). In certain preferred embodiments noise detection and subsequent control operations can be performed at high speed and low latency using wideband, wide dynamic range log converters. The logarithmic RF converters are designed to produce a voltage output proportional to the log of the RF power, enabling RF power detection over a wide dynamic range, for example, over about 5-10 decades (orders of magnitude).

[0050] In another embodiment part of the filtered signal after the second arm can be used to detect the repetition frequency or any of its harmonics for frep monitoring and/or feedback control.

[0051] By way of example, one such log converter is Analog Devices' AD8310 demodulating logarithm amplifier capable of maintaining good logarithmic conformance over an input dynamic range exceeding about nine decades, and a gain-bandwidth product of about 10^4 GHz. DC-440 MHz operation is specified, with some decrease in logarithmic conformance above about 100 MHz. One application of such amplifiers is the detection of short bursts of RF energy as short as tens of ns in duration. When used for high-speed control of the mode locked lasers, the combination of wide dynamic range and low latency can improve performance relative to control systems based on linear amplifiers and A/D and D/A conversion.

[0052] The RF power detected by the RF power meters is converted to a suitable voltage output which is further directed to the controller. The controller is configured to control the oscillator or amplifier pump laser. The controller can turn the amplifier off in case undesirable oscillator operation is detected, in order to prevent damage to any optical components in the system, and/or otherwise control the oscillator and/or amplifier. As another example, the oscillator pump current can be reduced is such a case.

[0053] The following examples are instructive for comparing low noise mode locked signals, for example, with f_{rep} near 100 MHz, with mode-locked signals degraded by double pulsing, q-switching, a random noise over a broadband frequency spectrum, or the like. The illustrated waveforms and spectra shown in Figs. 4a-1-4d-2 are similar to observations made with a digital oscilloscope and RF spectrum analyzer in a test arrangement corresponding to Fig. 3. The schematic illustrations are representative of the time domain and frequency information received.

[0054] *Low noise mode-locked operation*: Figs 4a-1 illustrates relatively low noise mode-locked operation as exemplified by the inverted oscilloscope traces. Fig 4a-2 shows the corresponding RF spectrum which includes f_{rep} 410 and 2frep.

[0055] *Double pulsing*: Figs 4b-1 illustrates double pulsing. The effect is difficult to detect from the time domain traces, but is apparent from the spiky frequency content 420 in Fig 4b-2. Notably, in the time domain the spacing between the multiple pulses is very small and difficult to discern.

[0056] *Q-switching*: Figs 4c-1 illustrates the presence of Q-switching in the time domain. It can be seen that the waveform is severely degraded and distorted relative to that of Fig. 4a-1. The waveform is representative of a sequence of mode-locked pulses contained in a more slowly varying Q-switched envelope generated at KHz frequencies (represented by the wide time separation in the plot). The effect is noticeable in Fig 4c-2 as having strong low frequency components 430 together with reduced power at frep 435 and in the second harmonic.

[0057] *Noisy mode-locked*: Fig 4d-1 illustrates erroneous pulse temporal shapes characterizable by high frequency spikes, in contrast to a smooth Gaussian like temporal profile shown in Figs 4a-1 and 4b-1. The frequency domain data of Fig. 4d-2 shows the

mode-locked signals and a nearly uniform noise (e.g.: white) noise spectrum 445 indicative of large and random fluctuations. The noise is well above zero power (horizontal axis) 440.

[0058] In an experiment using the high sensitivity arrangement described above, the background noise power caused by *double pulsing* was discriminated from the low noise mode-locked state. The dB difference was significantly above the specification for the log amplifier dB error allowing for such detection. Notably, the "double pulse" data was manifested by a narrow series of spectral spikes of relatively low amplitude and effectively undetectable with conventional domain observations. However, the relative increase in integrated noise power was detectable with the high-sensitivity, non-linear signal processing equipment. For example, an increase of at least about 2 dB was sufficient to identify a *double pulse* noise contribution characterized by having spectra similar to that in Fig. 4b-2. The *q-switching* and *noisy modes locked were* easily detected with the high sensitivity arrangement.

[0059] The two logarithmic power meters in the example of Fig 2 can essentially detect four states of laser operation. For the purpose of discussion we refer to the bandpass filtered RF power as RF_{ml}, and the low pass filtered RF power as RF_{noise}. The following states of operation may be identified from the respective signals:

[0060] If RF_{ml} is high and RF_{noise} is low or the ratio RF_{ml}/ RF_{noise} is maximized the laser is properly modelocked.

[0061] If RF_{ml} is high and RF_{noise} is high, the laser operates in a Q-switched mode-locked operation regime or is subject to persistent relaxation oscillations.

[0062] If RF_{ml} is low and RF_{noise} is high, the laser is Q-switching.

[0063] If RF_{ml} is low and RF_{noise} is low, the laser is oscillating in continuous wave mode or is essentially off. Those two modes of operation can be distinguished by monitoring the DC photocurrent of the detector as discussed above.

[0064] Moreover, a transition from single pulse to two pulse operation generally also affects the ratio RF_{ml}/ RF_{noise}. Thus the arrangement of Fig 2, with the increased sensitivity and bandwidth, improves detectability of a multiple pulse condition in which the mode-locked laser operates with two pulses per round – trip.

[0065] The determination of the state of the mode-locked laser can thus be reliably determined. By way of example, this can be done with a microcontroller which determines RF_{ml}/ RF_{noise}. High speed, low latency control can be achieved because for the determination of the state of the mode-locked laser it is not necessary to use A-D converter(s) which may introduce considerable latency that limits high speed control. It is to be understood, however, that in certain implementations high resolution A/D and/or D/A converters may be utilized with a suitable compromise in the control bandwidth, or for other auxiliary operations. In various preferred embodiments all-logic processing may be implemented with high speed comparators, DSPs, or FPGAs. The controller is capable of providing low latency signals representative of at least the relative power in the signal bandwidth and noise bandwidth. By way of example, a latency representing a response to an output of the noise detection unit may be in the range from about several hundred picoseconds to about 20 ns for certain high speed operations using present commercially available technology, and further reduced via custom logic design and optimization. One application of such high speed control is to enable rapid shutdown of the oscillator/amplifier if the noise and/or laser power exceeds a certain threshold. For example, the system may be configured to rapidly shutdown one or more pump diodes that pump the oscillator or amplifier. In some embodiments the system may also include a low delay modulator operatively coupled to the controller and mode-locked laser to attenuate laser power. In some embodiments the controller may be arranged to count or average a series of consecutive pulses prior to shutting down the pump so to improve noise immunity.

[0066] In various implementations, prior to interruption of mode-locked operation of a mode-locked oscillator, an increase in RF noise can be detected. The noise detection system illustrated above can protect optical components by turning the amplifier pump laser off before mode-locked operation is lost. This provides a very sensitive high speed and low latency method to protect high power laser systems from any possible damage, as amplifiers can be turned off to avoid damage. Such operation is beneficial for sensitive machining applications, for example in medical or micromachining applications for precise control of the fluence at a target material location.

[0067] Embodiments of the present invention are applicable to many types of mode-locked arrangements. The amplifier can be turned off and the micro-controller can be used to search for a stable operation of the mode-locked oscillator by changing the oscillator pump current or any other oscillator operating condition such as oscillator temperature polarization control etc. Once stable oscillator operation is ensured, the amplifier can be turned on again. U.S. Patents 6,839,363 (Lin), 6,693,927 (Horvath), and 7,668, 213 (Hoffman) discuss various techniques to establish and maintain mode-locking in actively or passively mode locked fiber lasers, and in various mode-locked solid state arrangements. A noise detection system of the present invention may be utilized to enhance the sensitivity of such systems.

[0068] For example, as illustrated in Fig 5a, a noise detection system can be included into the arrangement disclosed in U.S Patent 7,668,213 referenced above, which is hereby incorporated by reference in its entirety. In the example of Fig. 5a, the oscillator noise detection unit provides auxiliary outputs utilized by oscillator repetition rate monitoring device 51, and oscillator power monitor 52. Moreover, referring back to Fig. 1 of the present application, the controller of system 100 may be operatively connected to any or all of the monitoring/control elements for the pump current 53, diode temperature 54, or saturable absorber shown in Fig. 5b for use in a highly integrated arrangement.

[0069] Similarly, as illustrated in Fig. 5a, a noise detection system may readily be adapted for use with various arrangements disclosed in U.S. Patent 7,505,196 referenced above (incorporated by reference herein). As shown in FIG.7 of the '196 patent, various optical and electrical parameters can be monitored and controlled. Control of these parameters can be incorporated into the laser controller or into a system controller that is external to the laser controller and specific to the particular application. The laser controller has the ability to communicate with an external system controller over a communications link using communication interfaces common to computer communication, such as RS-232, IE-488, TCP/IP or CAN bus

[0070] The present detection system is particularly useful for determining the proper low noise operation of mode-locked comb systems, as excessive laser noise will affect the accuracy of any subsequent metrology applications. When excess laser noise is detected, the oscillator parameters can thus be re-optimized using the micro-controller for a service request. For example, U.S. Patent Application No. 12/955,759, ('759), entitled "Frequency comb system with large comb spacing", discloses a frequency comb system having a tunable GHz comb laser. Fig 6 of the present application schematically illustrates a noise detection arrangement according an embodiment of the present invention integrated in a system of the '759 application to monitor the tunable GHz laser 600. In this embodiment a slave laser, for example a quantum cascade laser is feedback stabilized to a selected comb line of the tunable GHz laser 600. The noise detection system together with the comb control system ensures that the tunable GHz laser 600 operates in a low-noise mode-locked state. By way of the slave laser control, any noise of the tunable GHz laser 600 can be transferred to the slave laser. A noise detection arrangement as described herein ensures that little or no excess noise of the tunable GHz laser 600 will affect the slave laser. The system may be easily interfaced to a communication network for remote diagnostics and adjustments.

[0071] For purposes of summarizing the present invention, certain aspects, advantages and novel features of the present invention are described herein. It is to be understood, however, that not necessarily all such advantages may be achieved in accordance with any particular embodiment Thus, the present invention may be embodied or carried out in a manner that achieves one or more advantages without necessarily achieving other advantages as may be taught or suggested herein.

[0067] The invention has been described in several embodiments. It is to be understood that the embodiments are not mutually exclusive, and elements described in connection with one embodiment may be combined with, or eliminated from, other embodiments in suitable ways to accomplish desired design objectives.

[0072] Thus, while only certain embodiments have been specifically described herein, it will be apparent that numerous modifications may be made thereto without departing from the spirit and scope of the invention. Further, acronyms are used merely to enhance the readability of the specification and claims. It should be noted that these acronyms are not intended to lessen the generality of the terms used and they should not be construed to restrict the scope of the claims to the embodiments described therein.

1. A laser based system, comprising:

a mode-locked oscillator generating optical pulses at a repetition frequency, f_{rep};

a noise detection unit comprising:

at least one optical detector that monitors optical pulses generated by the mode-locked oscillator and produces electrical signals in response to the optical pulses, said noise detection unit comprising a first filter to transmit signal power over a signal bandwidth which includes said repetition frequency, frep, and further comprising one or more additional filters to transmit power over a noise bandwidth that substantially excludes the repetition frequency, frep;

non-linear signal processing equipment to generate one or more signals representative of power in the signal bandwidth relative to power in the noise bandwidth; and

a controller which estimates the relative power in the signal bandwidth and in the noise bandwidth, and is configured to generate a signal for controlling at least an element of the laser based system based on the relative power.

2. The system of claim 1, wherein said first filter comprises a bandpass filter centered about frep.
3. The system of claim 1, wherein said one or more additional filters comprises a low pass filter with a frequency cutoff less than frep.
4. The system of claim 3, wherein said frequency cutoff of said low pass filter is as low as about $f_{rep}/2$.
5. The system of claim 1, wherein said noise detection unit comprises an optical tap coupled to said optical detector and configured to by extract a portion of the optical pulses.

6. The system of claim 1, wherein said non-linear signal processing equipment provides an available dynamic range of at least about 60 dB via signal compression.
7. The system of claim 6, wherein said non-linear signal processing equipment comprises a logarithmic converter.
8. The system of claim 6, wherein said dynamic range may be in the range from greater than 80 dB to about 100 dB.
9. The system of claim 1, wherein said controller comprises digital signal acquisition and signal processing equipment to provide for an estimate the relative power.
10. The system of claim 1, further comprising at one optical amplifier downstream from the mode-locked oscillator, and wherein said controller generates a signal to control the energy of a pump diode utilized to pump the mode-locked oscillator and/or the downstream optical amplifier.
11. The system of claim 1, wherein the controller is configured to generate a signal for control of the pump diode current, temperature, pressure, and/or position of an intra-cavity element of the mode-locked oscillator.
12. The system of claim 1, wherein said controller comprises high-speed digital circuitry to provide one or more signals representative of at least the relative power in the signal bandwidth and noise bandwidth, said controller generating said signals with a low-latency in the range from about several hundred ps to 20 ns.
13. The system of claim 1, wherein said system comprises an optical frequency comb generator, at least a portion of which comprises said mode-locked oscillator.
14. The system of claim 1, wherein said laser-based system configured as a portion of a frequency comb source for optical metrology.
15. The system of claim 1, wherein said laser-based system is configured as a portion of a laser-based micromachining system or laser surgery system.

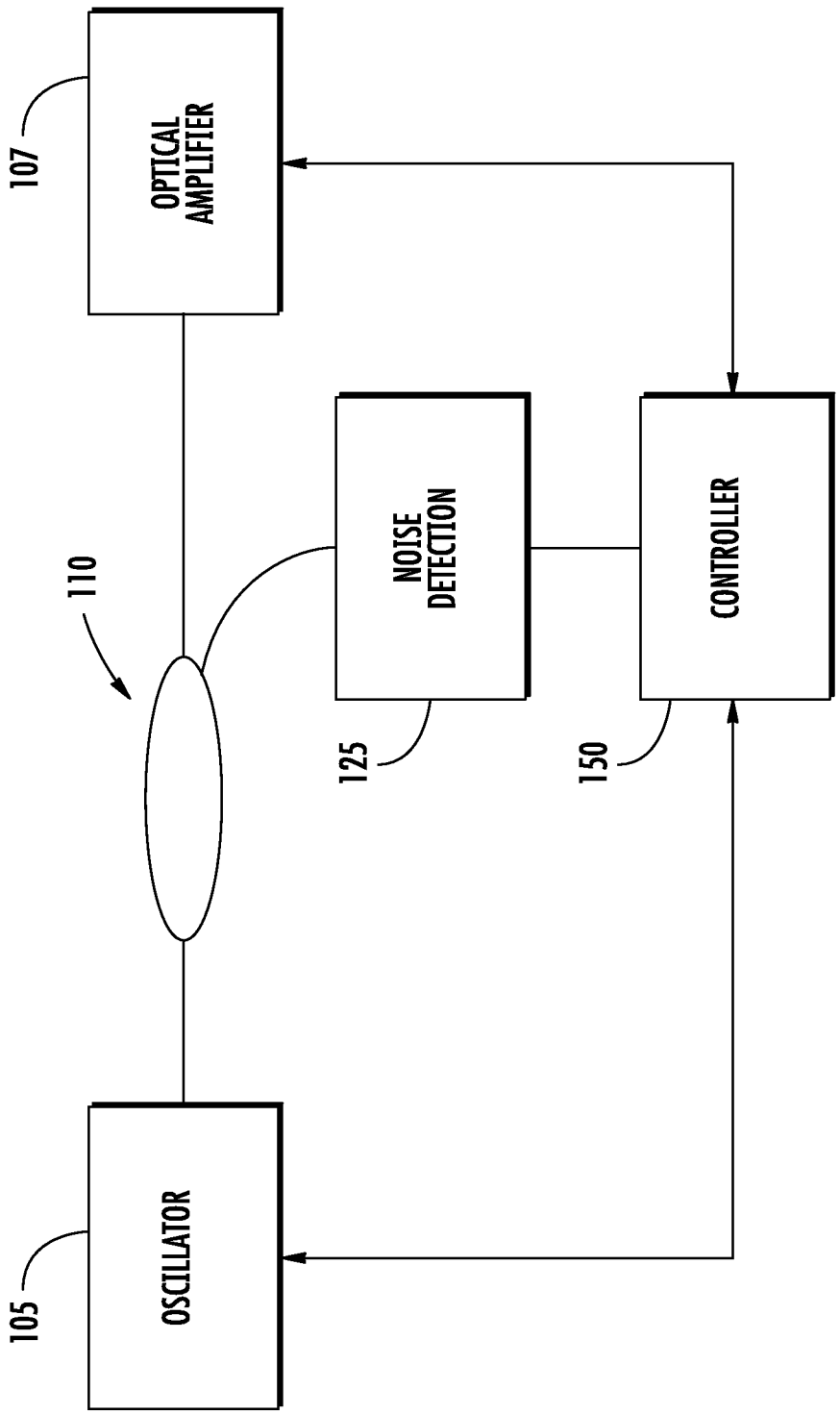

OPTICAL AMPLIFIER
107
NOISE DETECTION
125
CONTROLLER
150
110
OSCILLATOR
105
100

FIG. 1

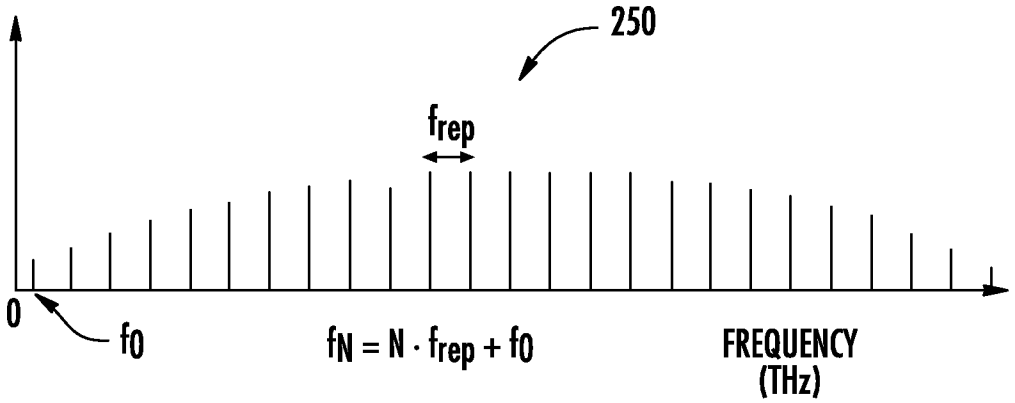


FIG. 2A

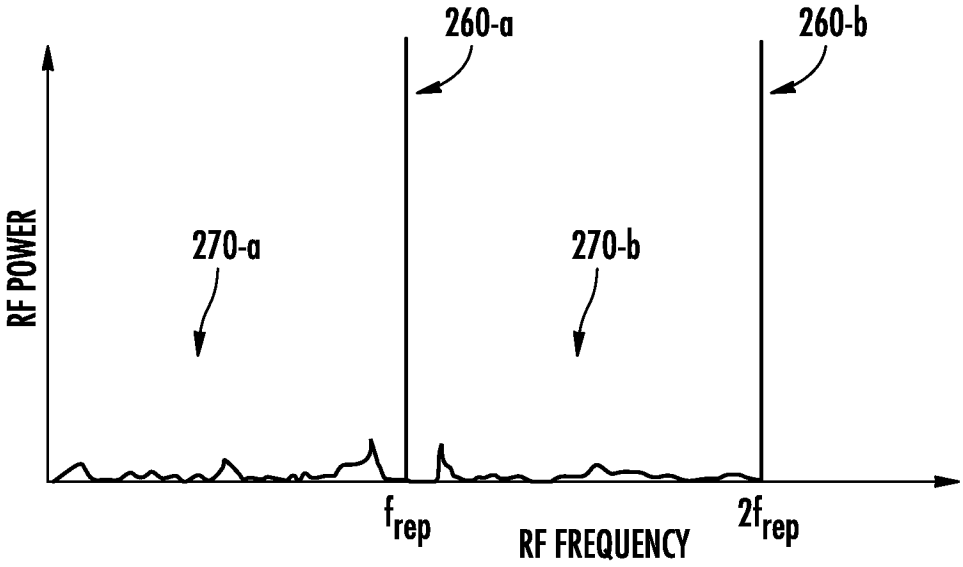


FIG. 2B

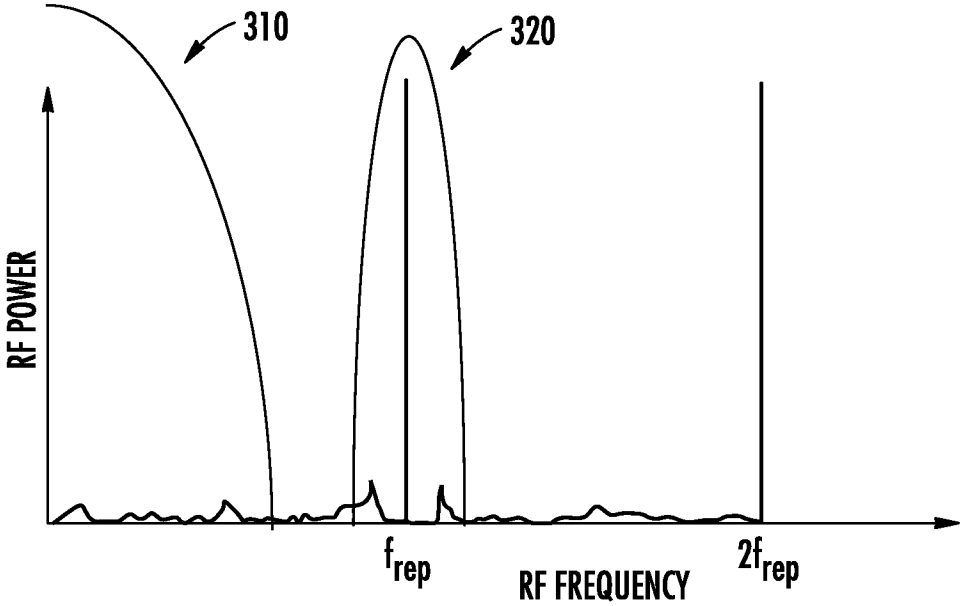


FIG. 2C

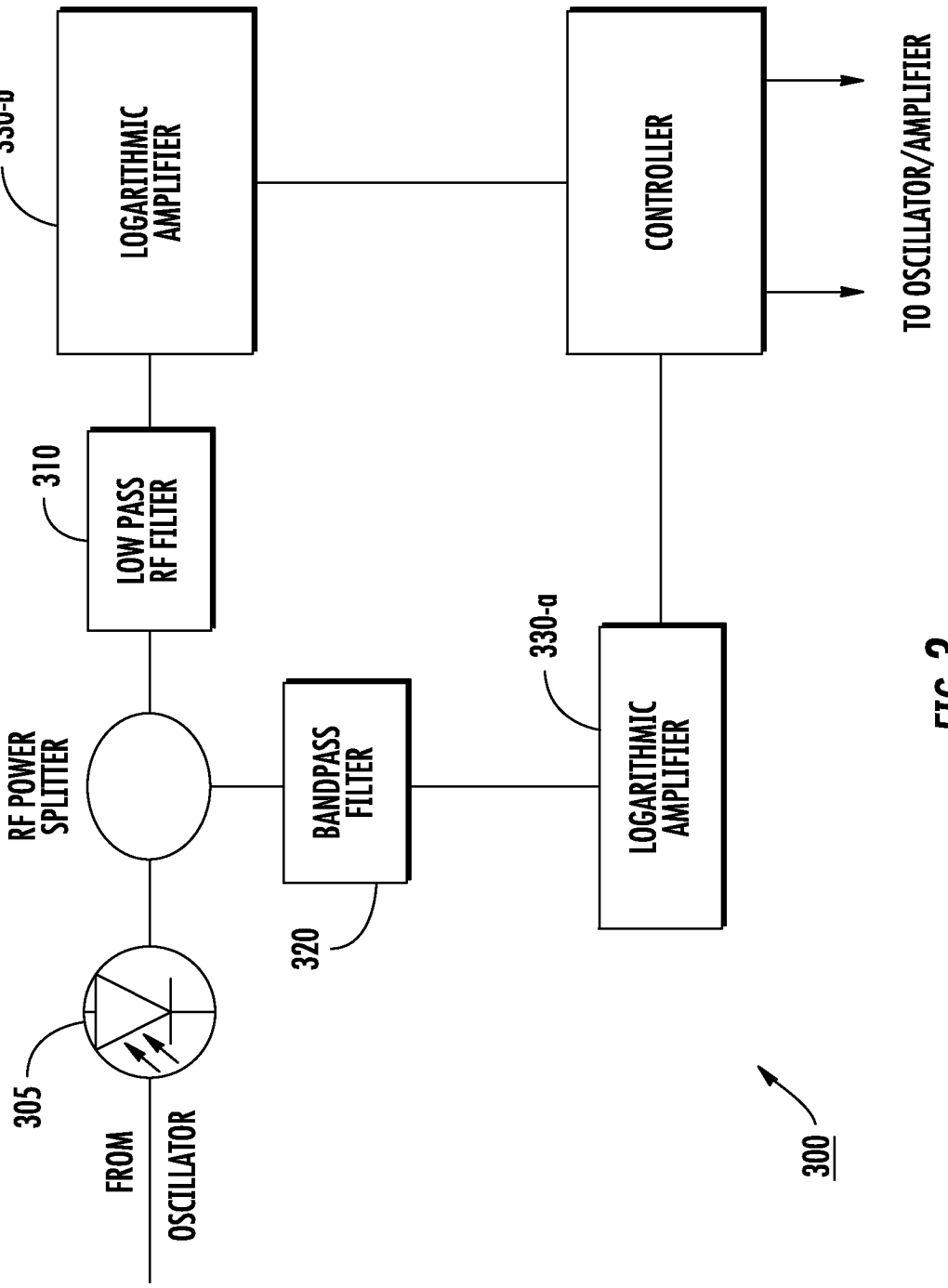

330-b
LOGARITHMIC AMPLIFIER
CONTROLLER
TO OSCILLATOR/AMPLIFIER
310
LOW PASS RF FILTER
330-a
RF POWER SPLITTER
BANDPASS FILTER
LOGARITHMIC AMPLIFIER
320
305
FROM OSCILLATOR
300

FIG. 3

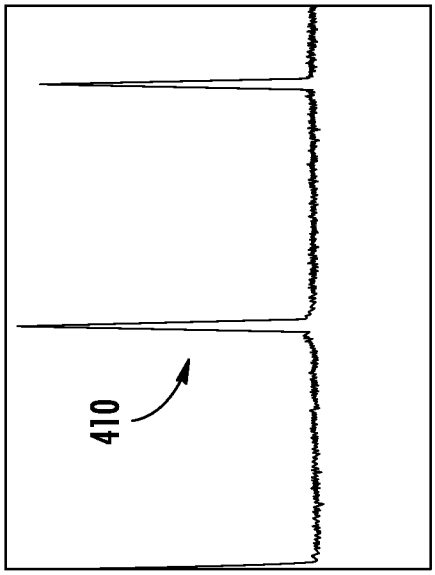


FIG. 4A-2

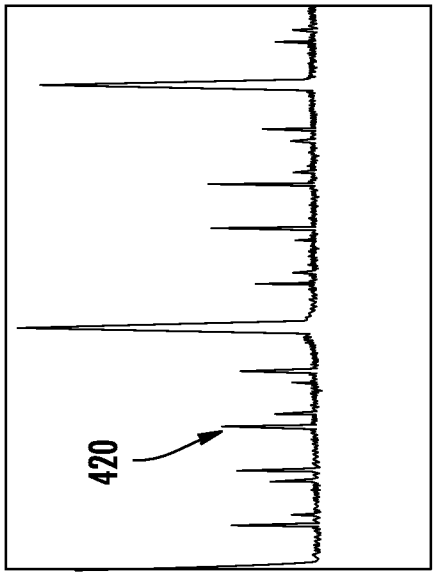


FIG. 4B-2

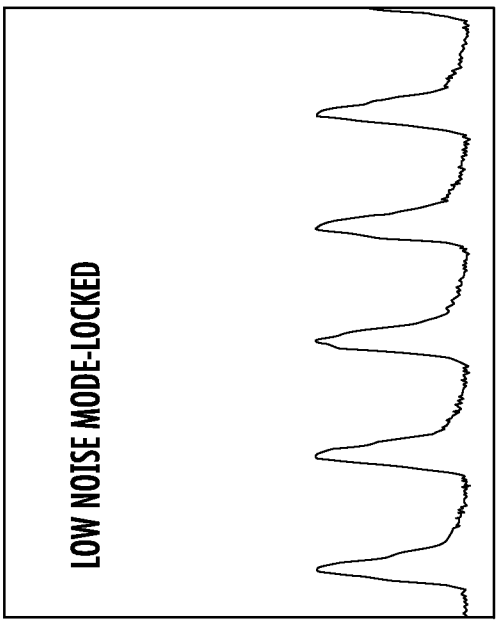


FIG. 4A-1

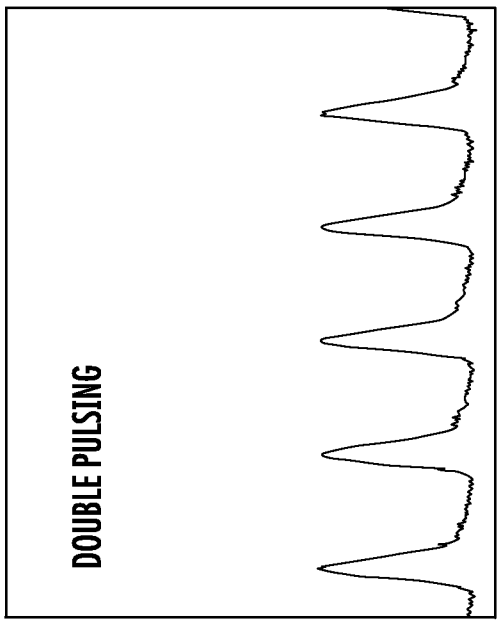


FIG. 4B-1

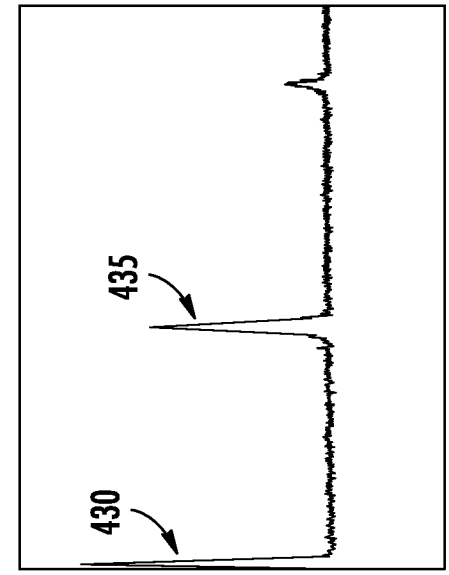


FIG. 4C-2

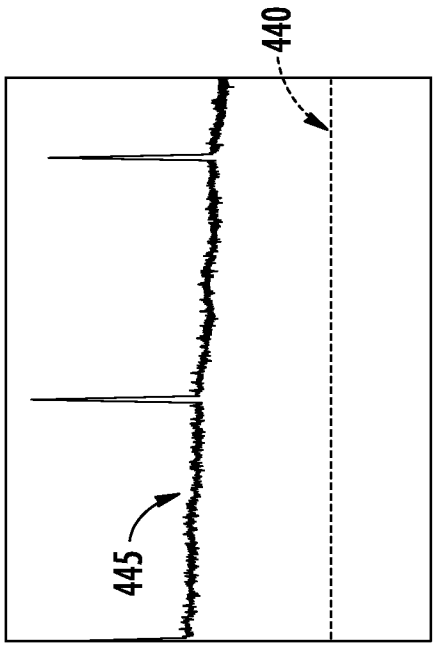


FIG. 4D-2

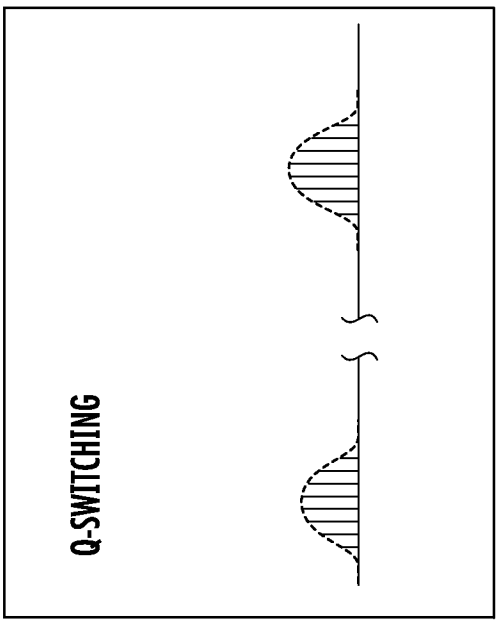


FIG. 4C-1

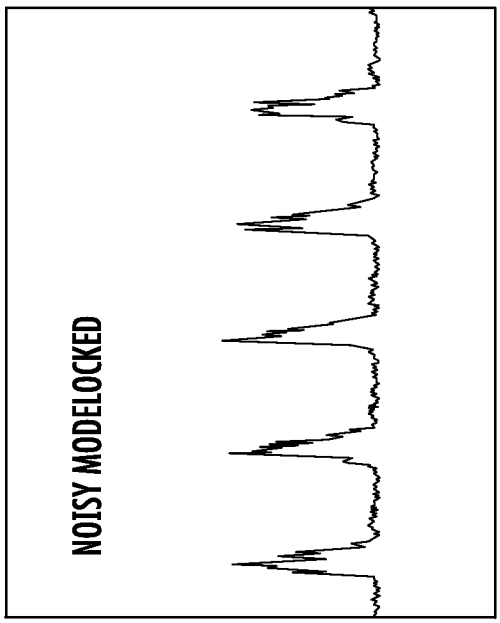


FIG. 4D-1

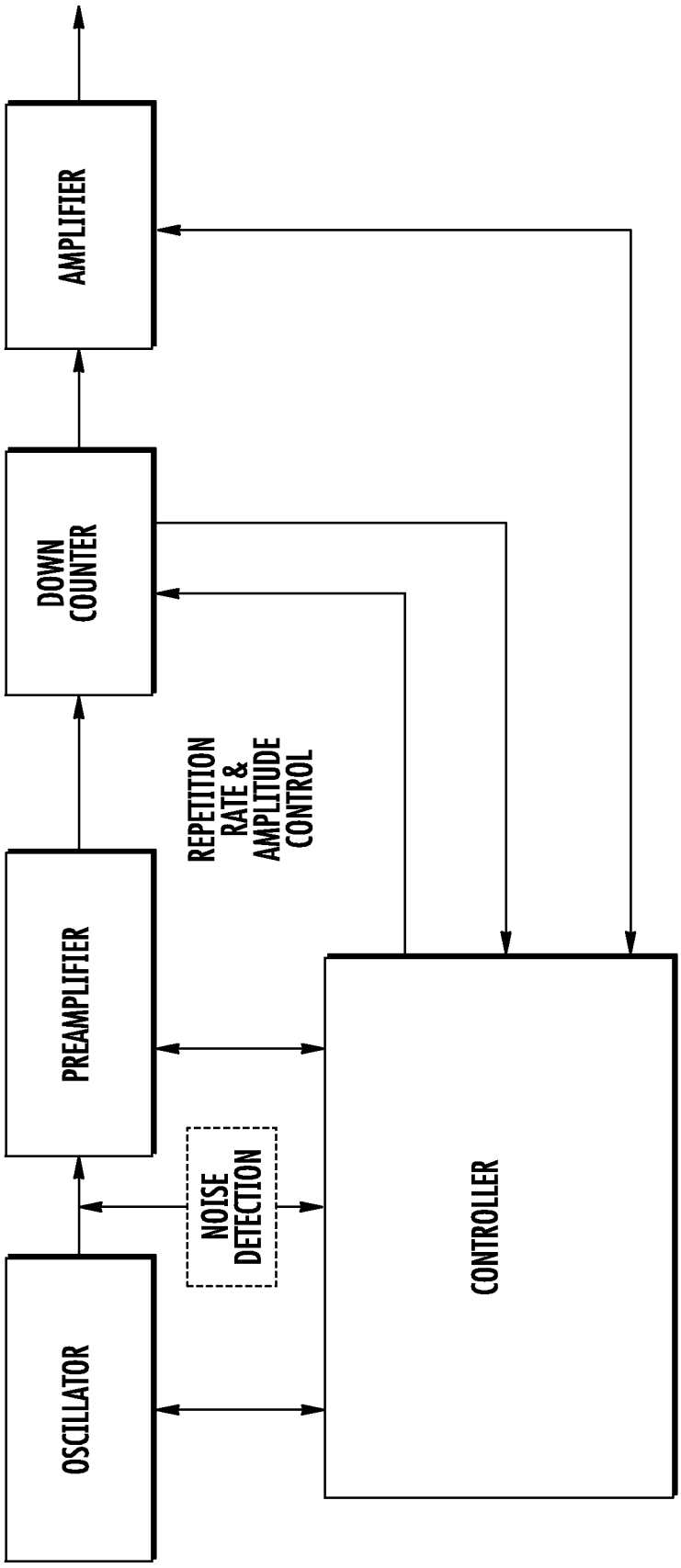

AMPLIFIER
DOWN COUNTER
PREAMPLIFIER
OSCILLATOR
NOISE DETECTION
CONTROLLER
REPETITION RATE & AMPLITUDE CONTROL
POWER CONTROL, POLARIZATION CONTROL, BEAM SHAPE CONTROL
REPETITION RATE & POWER MONITOR, POLARIZATION MONITOR, BEAM SHAPE MONITOR

FIG. 5A

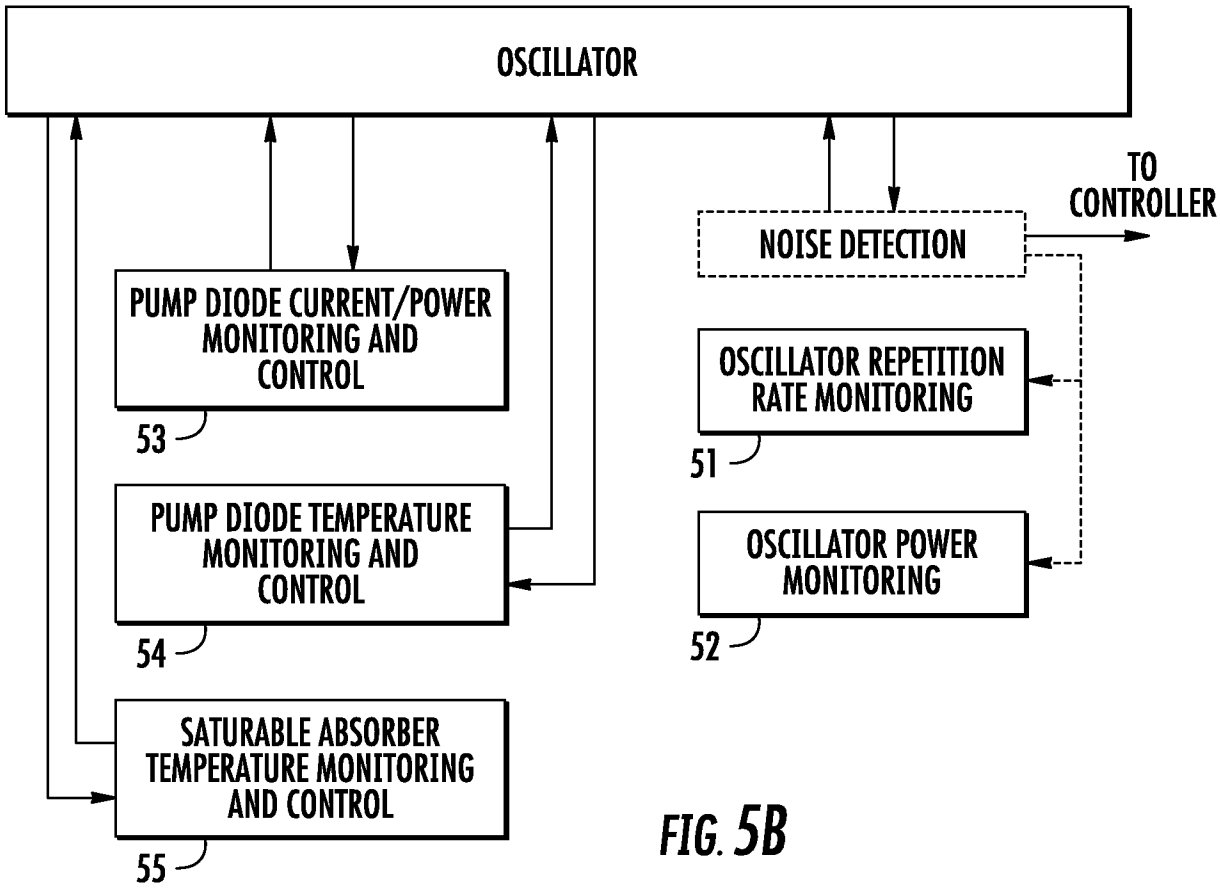

OSCILLATOR
TO CONTROLLER
NOISE DETECTION
PUMP DIODE CURRENT/POWER MONITORING AND CONTROL
53
OSCILLATOR REPETITION RATE MONITORING
51
PUMP DIODE TEMPERATURE MONITORING AND CONTROL
54
OSCILLATOR POWER MONITORING
52
SATURABLE ABSORBER TEMPERATURE MONITORING AND CONTROL
55

FIG. 5B

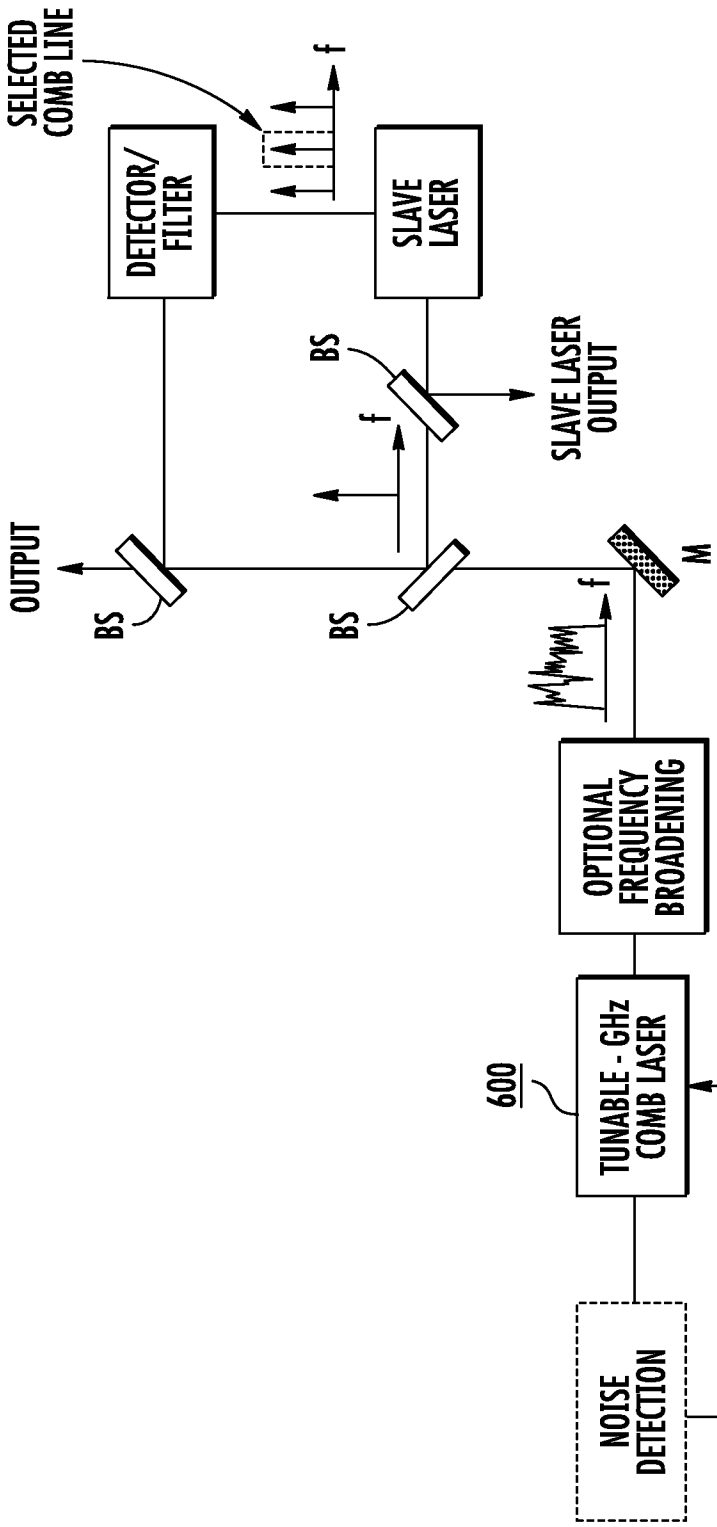

SELECTED COMB LINE
f
DETECTOR/ FILTER
SLAVE LASER
BS
f
SLAVE LASER OUTPUT
OUTPUT
BS
BS
M
f
OPTIONAL FREQUENCY BROADENING
600
TUNABLE - GHz COMB LASER
COMB CONTROL
NOISE DETECTION

FIG. 6

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2013/065448

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - H01S 3/10 (2014.01)
USPC - 372/18
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)
IPC(8) - H01S 3/00, 10, 13 (2014.01)
USPC - 372/18, 21, 29.01, 29.011, 29.02, 29.021, 30, 38.01, 38.02, 38.08

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
CPC - H01S 3/00, 0014, 10, 10015, 1106, 13, 1305 (2014.02)

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2002/0176452 A1 (LIN et al) 28 November 2002 (28.11.2002) entire document	1-15
Y	US 2003/0219069 A1 (CHEN et al) 27 November 2003 (27.11.2003) entire document	1-15
Y	US 2010/0061568 A1 (RASMUSSEN) 11 March 2010 (11.03.2010) entire document	1-15
Y	US 2006/0280505 A1 (VARSHNEYA et al) 14 December 2006 (14.12.2006) entire document	5
Y	US 2009/0284828 A1 (SOSABOWSKI et al) 19 November 2009 (19.11.2009) entire document	13, 14

☐ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"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	Date of mailing of the international search report
23 June 2014	14 JUL 2014
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer: Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774