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Foltynowicz

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(54) **HIGH-ENERGY, BROADBAND, RAPID TUNING FREQUENCY CONVERTER**

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(51) **Int. Cl.**

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H01S 3/00	(2006.01)
G02F 1/35	(2006.01)
H01S 3/23	(2006.01)

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CPC ***H01S 3/0092*** (2013.01); ***G02F 1/39*** (2013.01); *G02F 2001/3542* (2013.01); *G02F 2001/392* (2013.01); *H01S 3/2391* (2013.01)

USPC **372/28**

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CPC H01S 5/14; H01S 5/10; H01S 5/02438; H01S 3/2391; G02F 2001/392; G02F 2001/3542; G02F 1/39

USPC 372/21, 28, 92, 94

See application file for complete search history.

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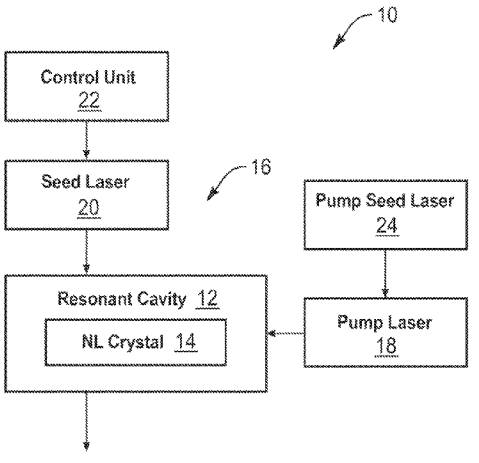
Primary Examiner — Tuan Nguyen

(57) **ABSTRACT**

An Optical Parametric Oscillator (OPO) capable of rapid or broadband frequency tuning by non-mechanical or mechanical means includes a resonant cavity with one or more non-linear crystals in an optical path thereof. The non-linear crystals may be driven by actuators. A pump laser pulse is transmitted into the resonant cavity with one or more seed beams having a desired wavelength. The output beam from the resonant cavity may have the same center wavelength as the one or more seed beams which may be modulated at a frequency larger than that of the pump laser, or the inverse of the pulse duration. The OPO may be used in Light Detection And Ranging (LIDAR) or Differential Absorption LIDAR (DIAL) analysis by intra-pulse modulation of output to measure absorption at multiple frequencies for each pulse of a pump beam. Sum Frequency Generator configurations may be suitable for narrow and broadband UV generation.

18 Claims, 11 Drawing Sheets



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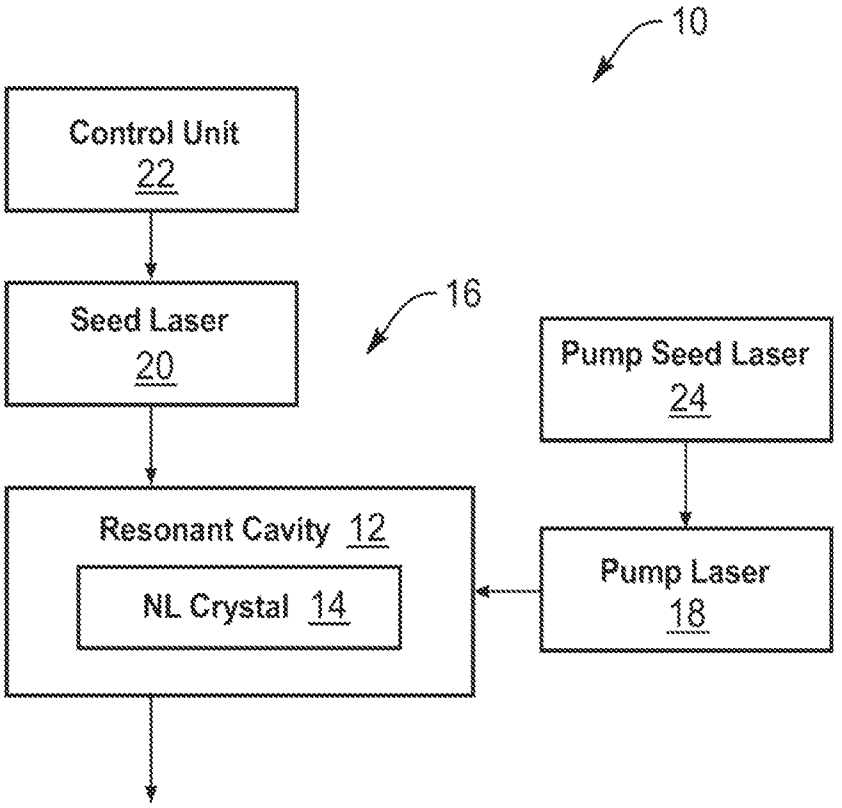


Figure 1

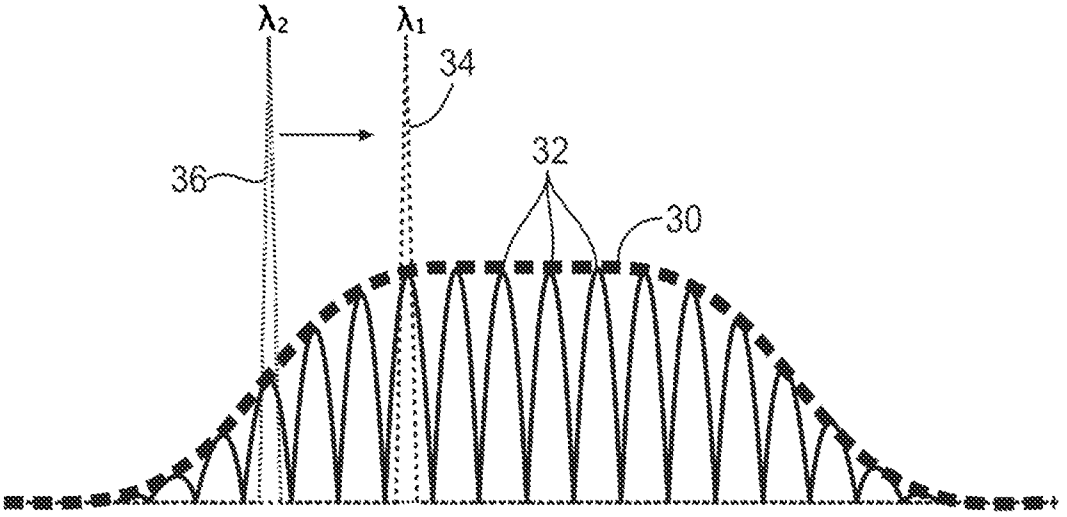
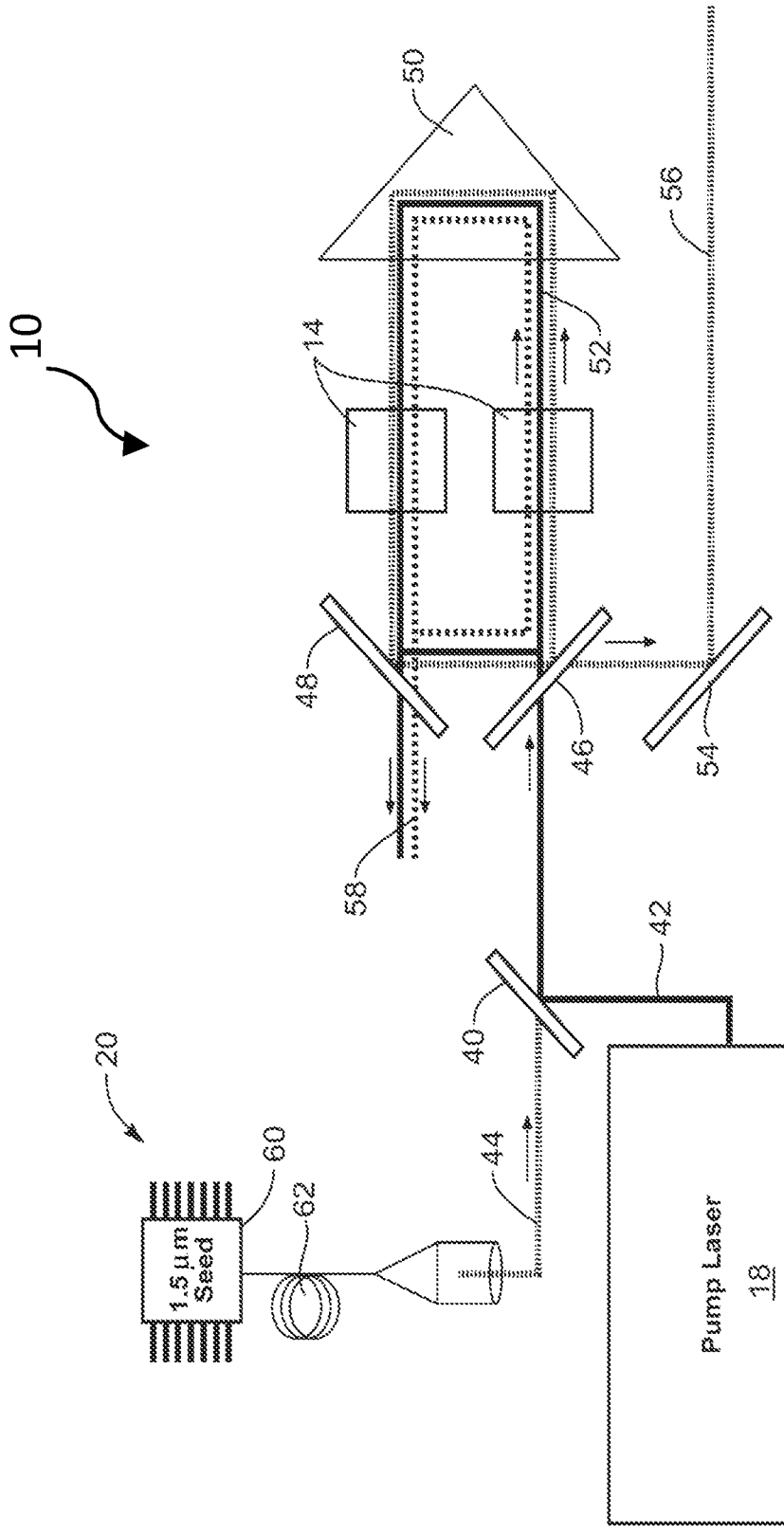


Figure 2



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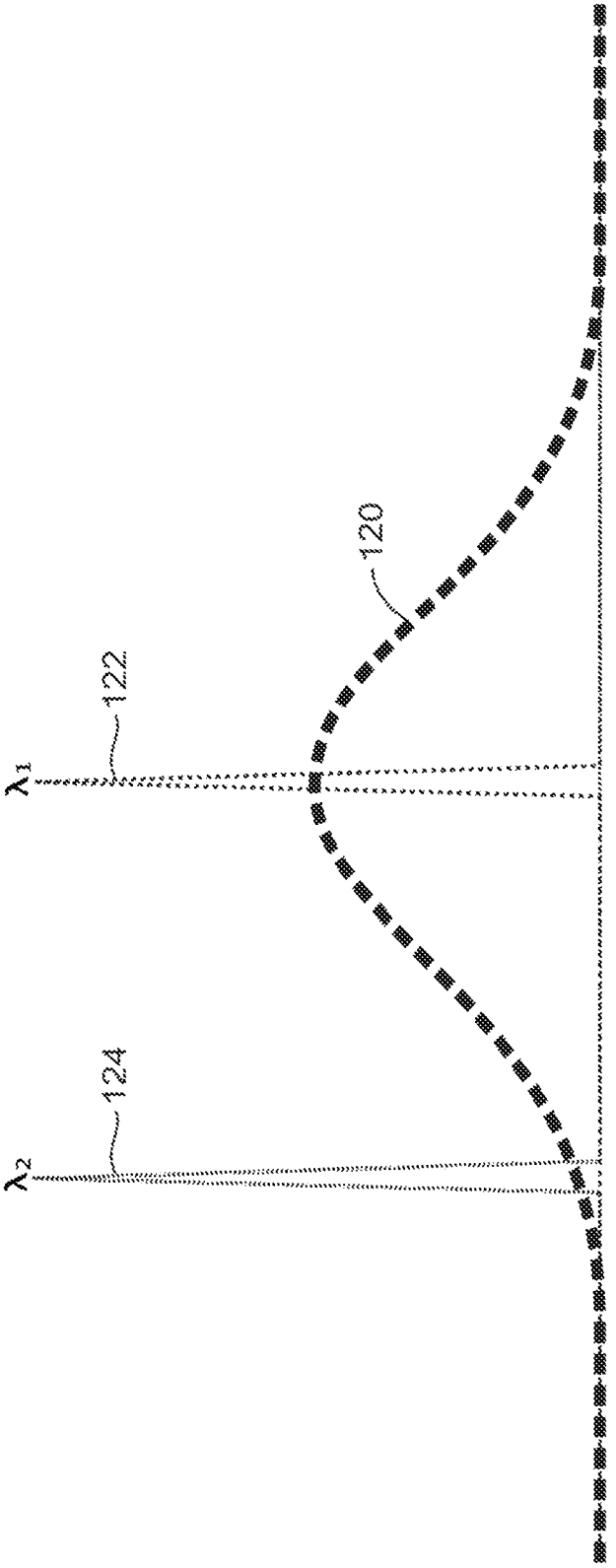

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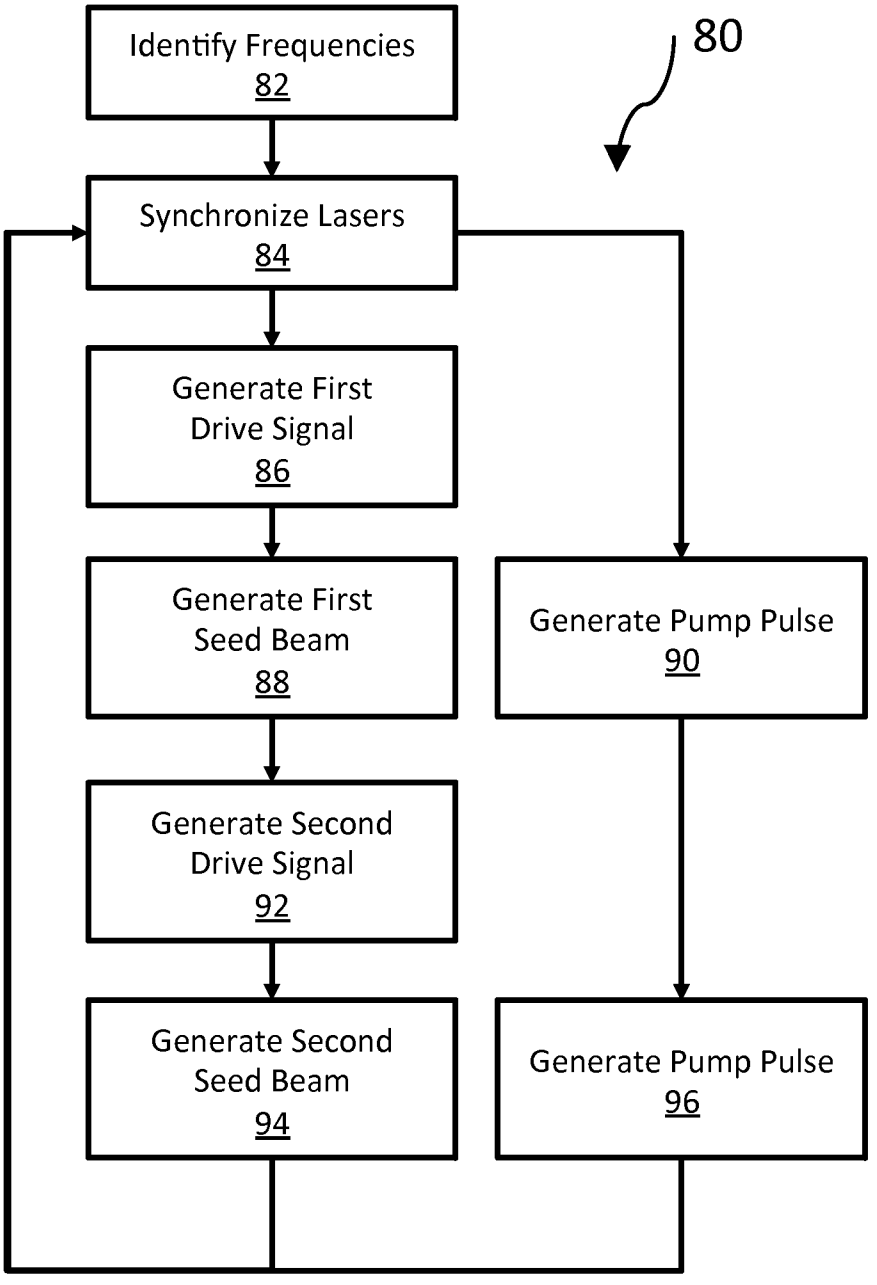

Identify Frequencies
82
80
Synchronize Lasers
84
Generate First
Drive Signal
86
Generate First
Seed Beam
88
Generate Second
Drive Signal
92
Generate Second
Seed Beam
94
Generate Pump Pulse
90
Generate Pump Pulse
96

Figure 5

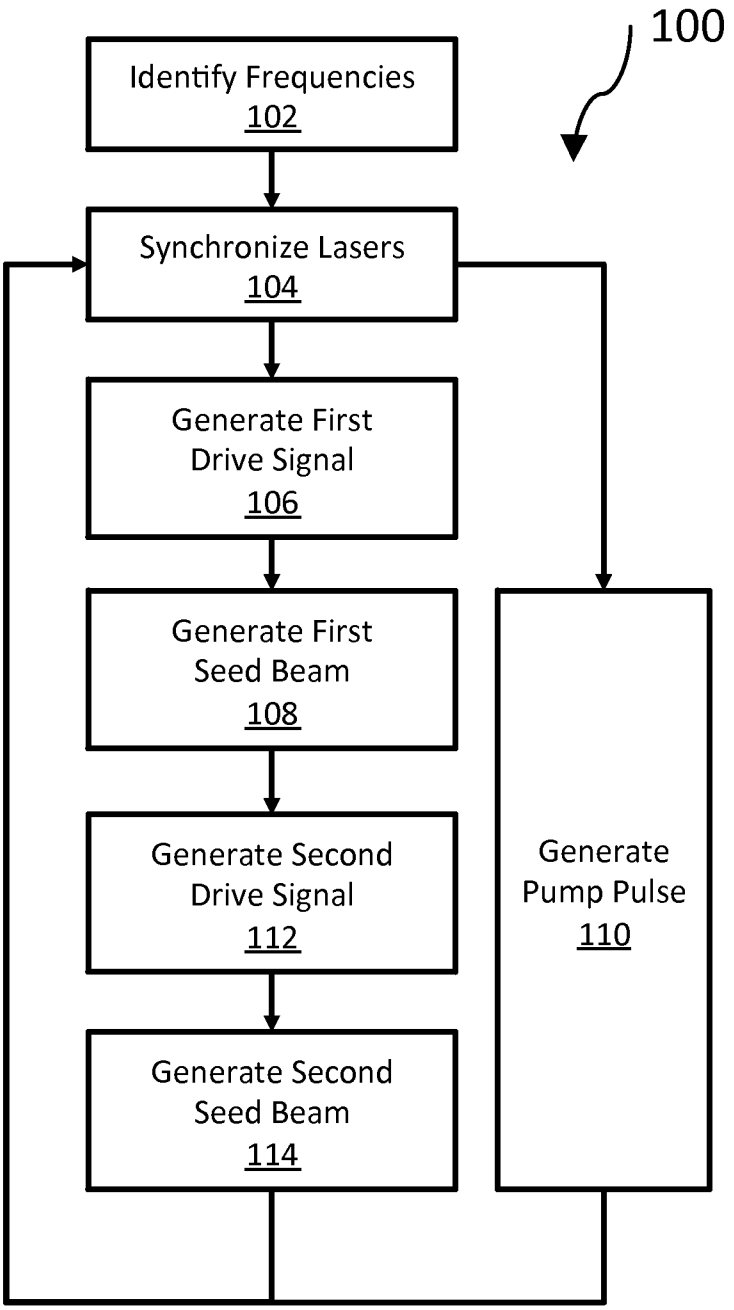
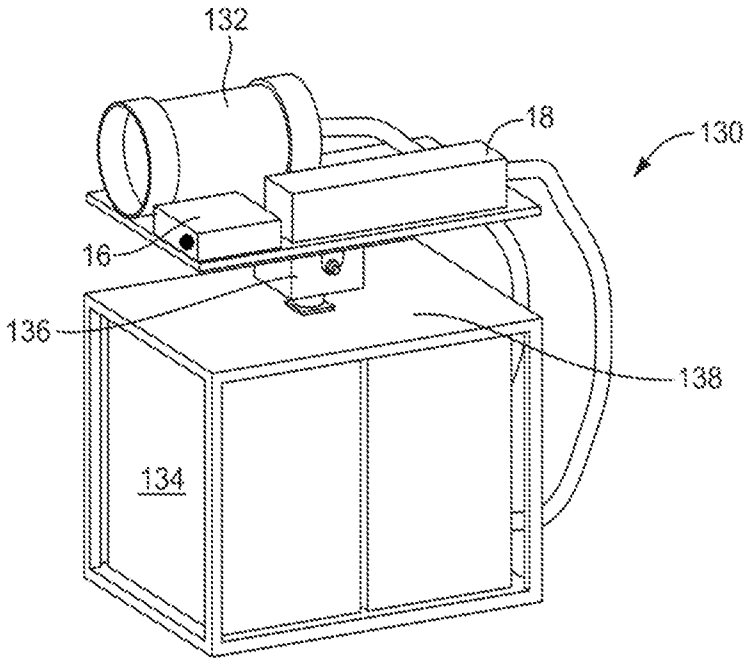

100
Identify Frequencies
102
Synchronize Lasers
104
Generate First
Drive Signal
106
Generate First
Seed Beam
108
Generate Second
Drive Signal
112
Generate Second
Seed Beam
114
Generate
Pump Pulse
110

Figure 6



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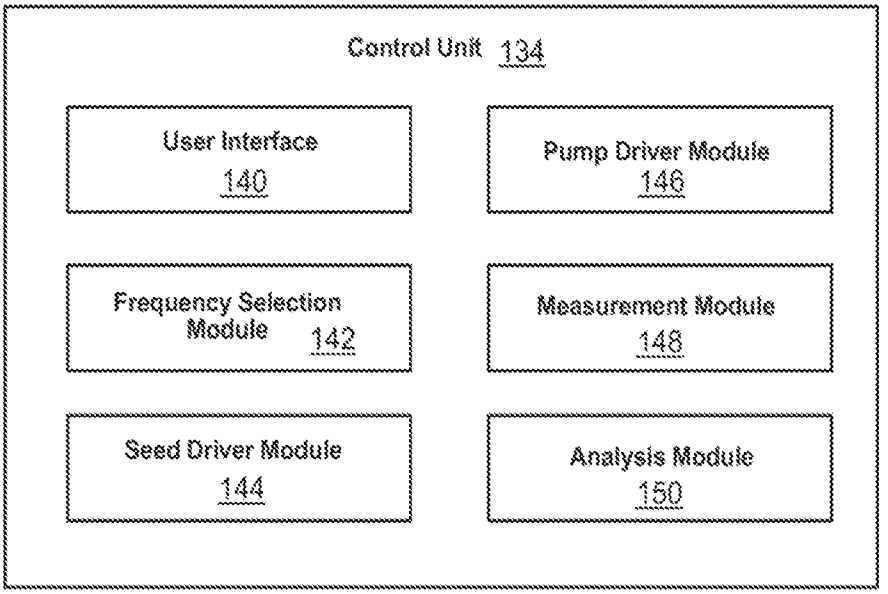

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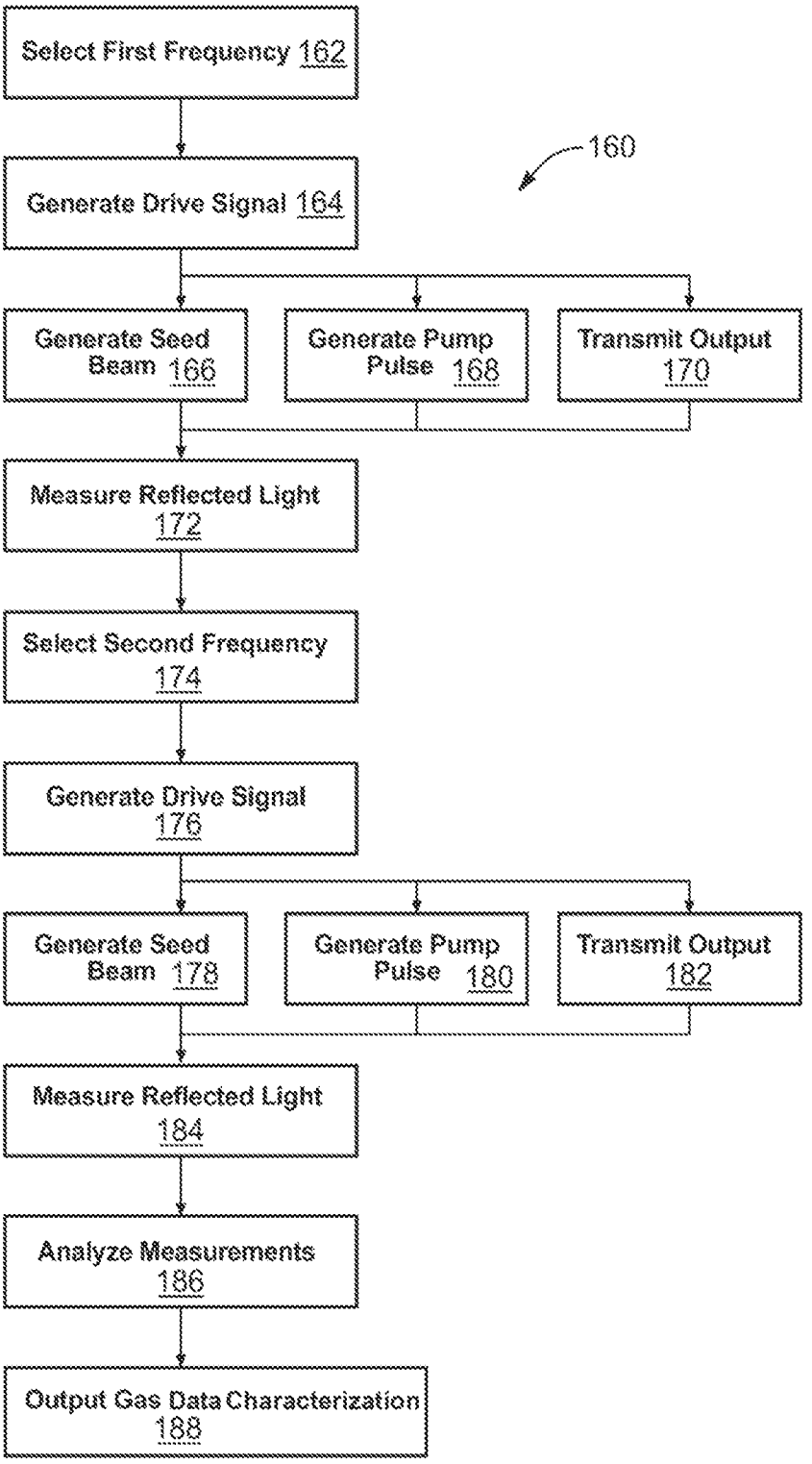
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160
Generate Drive Signal 164
Generate Seed Beam 166
Generate Pump Pulse 168
Transmit Output 170
Measure Reflected Light 172
Select Second Frequency 174
Generate Drive Signal 176
Generate Seed Beam 178
Generate Pump Pulse 180
Transmit Output 182
Measure Reflected Light 184
Analyze Measurements 186
Output Gas Data Characterization 188

Figure 9

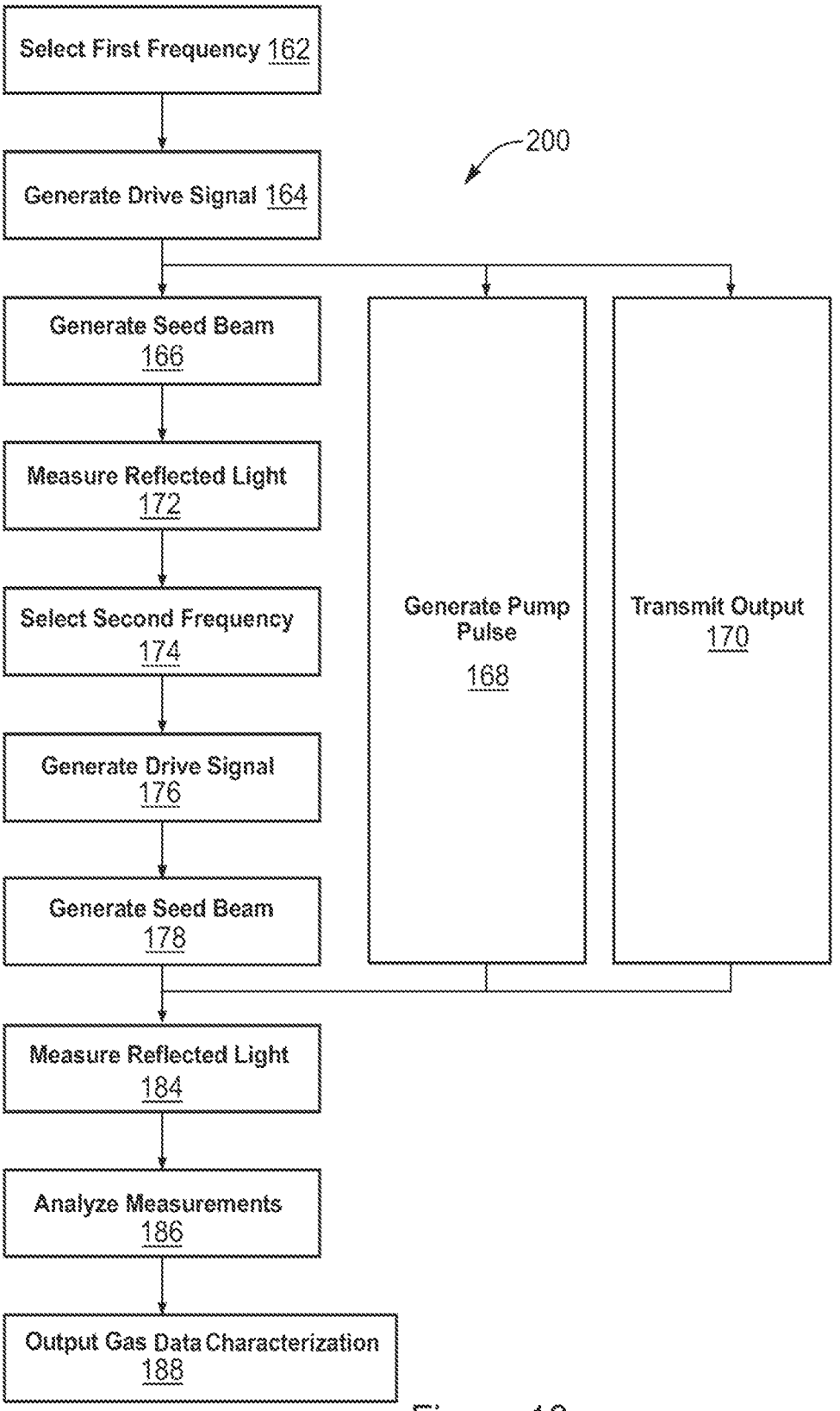

Select First Frequency 162
200
Generate Drive Signal 164
Generate Seed Beam 166
Measure Reflected Light 172
Select Second Frequency 174
Generate Drive Signal 176
Generate Seed Beam 178
Generate Pump Pulse 168
Transmit Output 170
Measure Reflected Light 184
Analyze Measurements 186
Output Gas Data Characterization 188

Figure 10

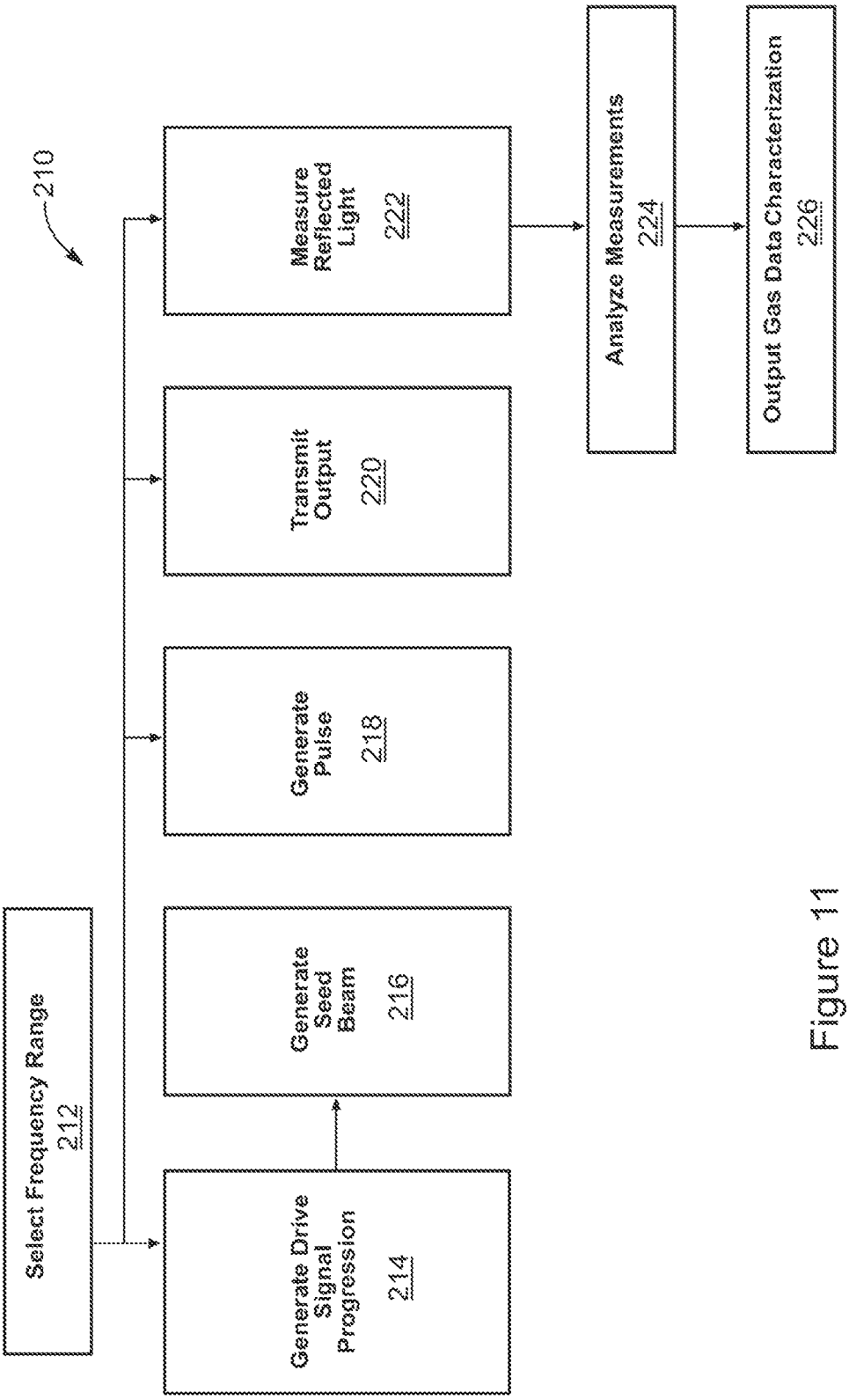
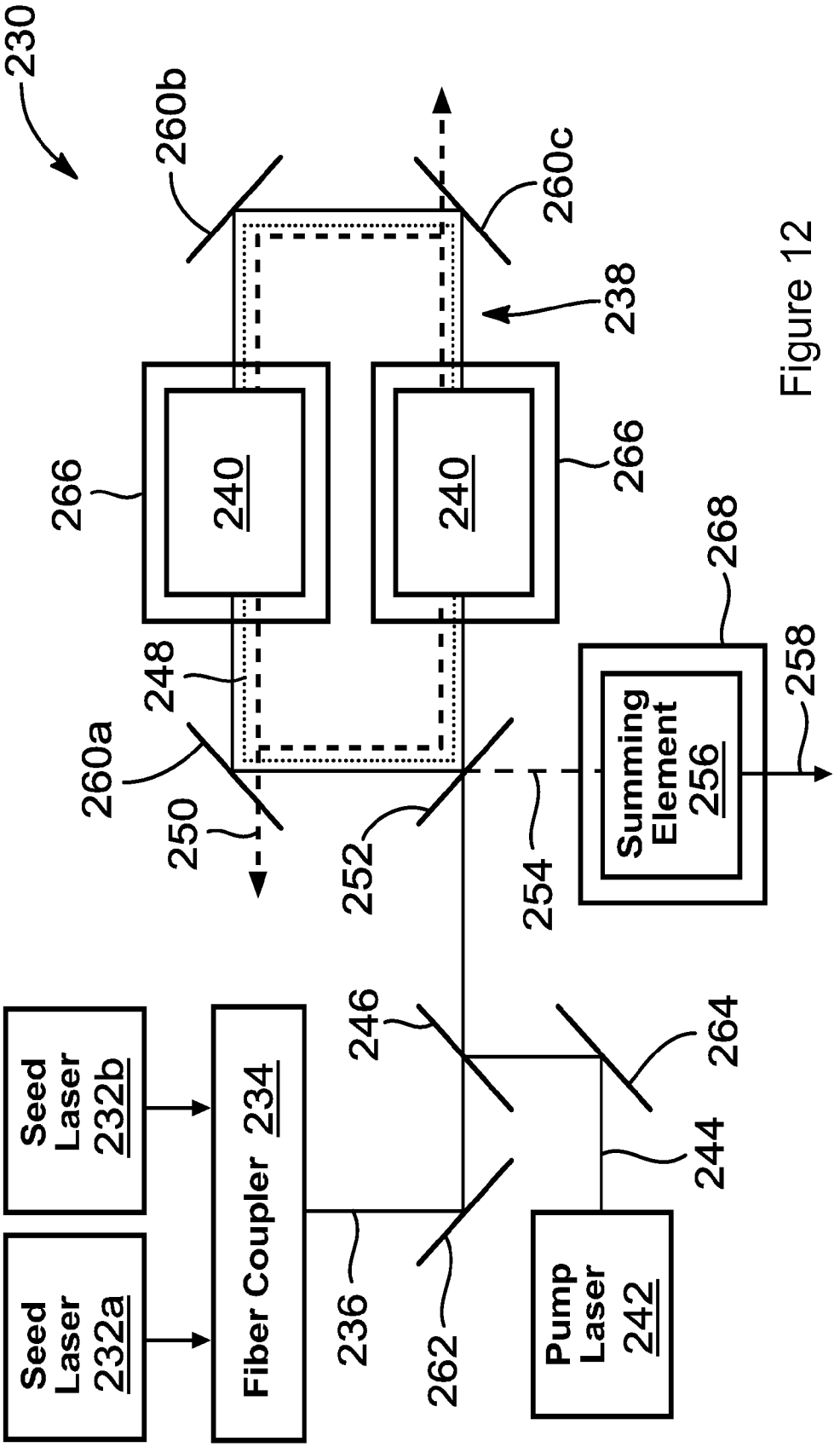

210
Select Frequency Range
212
Generate Drive Signal Progression
214
Generate Seed Beam
216
Generate Pulse
218
Transmit Output
220
Measure Reflected Light
222
Analyze Measurements
224
Output Gas Data Characterization
226

Figure 11


230
260b
260c
238
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240
240
266
268
248
258
260a
250
252
254
Summing Element 256
Seed Laser 232b
Seed Laser 232a
Fiber Coupler 234
246
264
244
236
262
Pump Laser 242

Figure 12

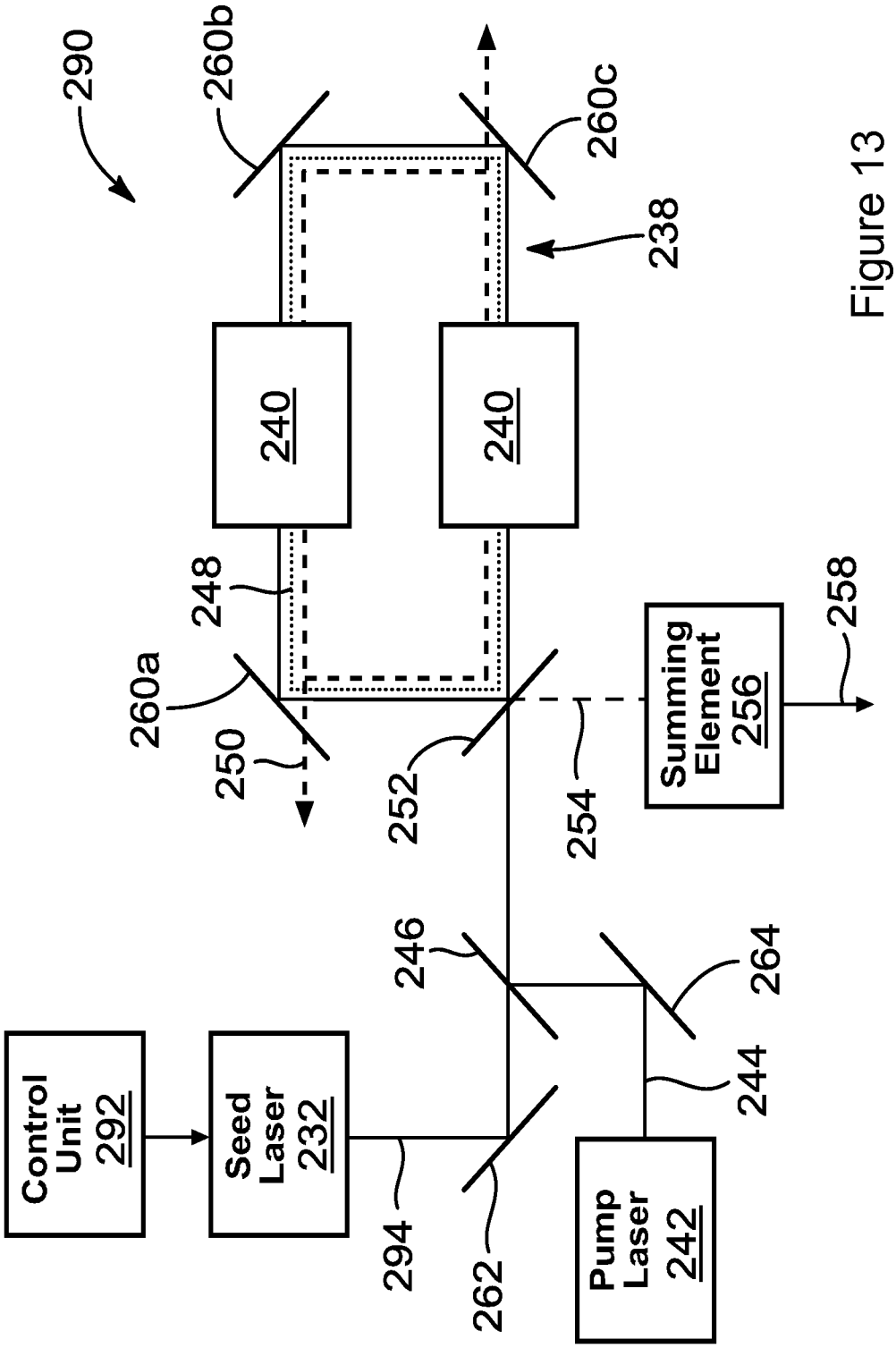
290
260b
260c
238
240
240
248
260a
250
252
254
Summing Element 256
258
246
264
244
Control Unit 292
Seed Laser 232
294
262
Pump Laser 242

Figure 13

HIGH-ENERGY, BROADBAND, RAPID TUNING FREQUENCY CONVERTER

RELATED APPLICATIONS

This application is a continuation in part of U.S. patent application Ser. No. 13/160,737, filed Jun. 15, 2011 and entitled OPTICAL PARAMETRIC OSCILLATOR WITH RAPID NON-MECHANICAL FREQUENCY TUNING, which claims the benefit of U.S. Provisional Application 61/360,293, filed Jun. 30, 2010 and entitled METHOD AND SYSTEM FOR NON-MECHANICAL RAPID TUNING OF AN OPTICAL PARAMETRIC OSCILLATOR, both of which are incorporated herein by reference in their entirety.

TECHNICAL FIELD

This invention relates to apparatuses, methods, and systems for tuning optical beams, and in particular, to apparatuses, methods, and systems for generating high-pulse energies with an ability to change wavelengths.

SUMMARY

The present disclosure in aspects and embodiments describe devices, systems, and methods for a high-energy, broadband, rapid tuning frequency generator that may be embodied as an optical parametric oscillator, (OPO), especially in light regions from the near infrared (NIR) to the ultraviolet (UV).

In embodiments, a laser system includes a pump laser configured to generate a pump beam having a pump wavelength and a pulse repetition frequency (PRF); a resonant cavity positioned to receive the pump beam; a non-linear crystal positioned within the resonant cavity such that the non-linear crystal and resonant cavity have a band of lasing wavelengths including wavelengths other than the pump wavelength, the non-linear crystal operable to output a signal beam in response to the pump beam; a seed laser positioned to emit a seed signal into the resonant cavity, the seed signal having a seed wavelength and the seed wavelength being within the band of lasing wavelengths; a seed laser controller electrically coupled to the seed laser and programmed to modulate the seed wavelength at the PRF of the pump laser; and a sum frequency generator (SFG) positioned to receive a portion of the pump beam and a portion of the signal beam, the SFG operable to output an output beam in response to the portion of the pump beam and the portion of the signal beam.

In another embodiment, the output beam can be modulated at a frequency between about 10 Hz and about 1 GHz. In another embodiment, the output beam is an ultraviolet (UV) beam with a wavelength that is modulated in a band from about 0.3 to about 0.5 nm.

In another embodiment, the non-linear crystal is fixed relative to the resonant cavity.

In another embodiment, the seed laser includes a first seed laser configured to emit a first seed signal having a first seed wavelength and a second seed laser configured to emit a second seed signal having a second seed wavelength, both the first and second seed lasers positioned to emit their respective signals into the resonant cavity, and both the first and second seed wavelengths being within the band of lasing wavelengths.

In another embodiment, the laser system further includes a crystal actuator coupled to the non-linear crystal. In another embodiment the system further includes a crystal actuator controller electrically coupled to the crystal actuator, the crystal actuator controller programmed to modulate the output beam by driving the crystal actuator.

In another embodiment the system further includes an SFG actuator controller electrically coupled to an SFG actuator, the SFG actuator controller programmed to modulate the output beam by driving the SFG actuator.

In another embodiment, the output beam is an ultraviolet (UV) beam with a wavelength that is modulated in a band from about 0.5 to about 4 nanometers.

In other embodiments, a method for operating a laser includes generating a pump beam at a pump wavelength and a pump pulse repetition frequency (PRF); transmitting the pump beam into a resonant cavity having a non-linear crystal in an optical path thereof, the non-linear crystal operable to emit a signal beam in a band of lasing wavelengths that includes wavelengths different from the pump wavelength; generating a seed beam having a seed wavelength lying within the band of lasing wavelengths; modulating the seed wavelength at a frequency greater than or equal to the pump PRF; transmitting the seed beam into the resonant cavity; transmitting a portion of the signal beam and a portion of the pump beam into a sum frequency generator (SFG); and outputting an output beam from the SFG.

In another embodiment, modulating the seed wavelength causes a corresponding modulation of an output wavelength of the output beam.

In another embodiment, the output beam is a UV beam and modulating the seed wavelength causes a corresponding modulation of the UV beam in a band between about 0.3 and 0.5 nanometers wide.

In another embodiment, generating the seed beam includes activating a laser diode; and modulating the seed wavelength includes modulating current supplied to the laser diode.

In another embodiment, the output beam can be modulated at a frequency between about 10 Hz and about 1 GHz (e.g., 1, 2, 3, 4, 5, 6, 7, 8, 9, or 10 GHz).

A method for operating a laser described in the embodiments above includes: generating a pump beam with a pump beam wavelength at a pump pulse repetition frequency (PRF); transmitting the pump beam into a resonant cavity having a non-linear crystal in an optical path thereof, the non-linear crystal being operable to emit a signal beam in a band of lasing wavelengths that includes wavelengths different from the pump beam wavelength; generating a first seed beam having a first seed wavelength lying within the band of lasing wavelengths; generating a second seed beam having a second seed wavelength lying within the band of lasing wavelengths, the second seed wavelength being different from the first seed wavelength; transmitting the first and second seed beams into the resonant cavity; transmitting a portion of the signal beam and a portion of the pump beam into a sum frequency generator (SFG); outputting an output beam having an output beam wavelength from the SFG; and modulating the output beam wavelength by actuating the non-linear crystal.

In another embodiment of a method, modulating the output beam wavelength includes actuating the non-linear crystal effectively to modulate the output beam wavelength at a frequency greater than or equal to the pump PRF.

In another embodiment of a method for operating a laser, actuating the non-linear crystal includes actuating the non-linear crystal effective to modulate the signal beam between the first seed wavelength and the second seed wavelength.

In another embodiment, a method for operating a laser further includes actuating the SFG in correspondence with actuation of the non-linear crystal.

In another embodiment of a method for operating a laser, the output beam is a UV beam and actuating the non-linear crystal includes actuating the non-linear crystal effective to modulate the wavelength of the UV beam over a range from about 0.5 to about 4 nanometers.

In another embodiment of the present disclosure, a gas characterization system includes: a pump laser configured to generate a pump beam having a pump wavelength at a pulse repetition frequency (PRF); a resonant cavity positioned to receive the pump beam; a non-linear crystal positioned within the resonant cavity such that the non-linear crystal and resonant cavity have a band of lasing wavelengths including wavelengths other than the pump wavelength, the non-linear crystal operable to output a signal beam in response to the pump beam; a seed laser positioned to emit a seed signal into the resonant cavity, the seed signal having a seed wavelength being within the band of lasing wavelengths; a seed laser controller electrically coupled to the seed laser and programmed to modulate the seed wavelength at a frequency at least as great as the PRF; a sum frequency generator (SFG) positioned to receive a portion of the pump beam and a portion of the signal beam, the SFG operable to output an output beam in response to the portion of the pump beam and the portion of the signal beam; a detector configured for receiving a reflected portion of the output beam from a region of interest; a measurement module configured to receive an output from the detector and produce a measurement of the reflected portion of the output beam; and an analysis module configured to analyze the measurement from the measurement module and characterize a gas in the region of interest.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing features of the present invention will become more fully apparent from the following description and appended claims, taken in conjunction with the accompanying drawings. Understanding that these drawings depict only typical embodiments of the invention and are, therefore, not to be considered limiting of its scope, embodiments will be described with additional specificity and detail through use of the accompanying drawings in which:

FIG. **1** is a schematic block diagram of an embodiment of an OPO system in accordance with the present disclosure;

FIG. **2** is a plot of the gain bandwidth and resonant modes of an OPO;

FIG. **3** is a schematic block diagram of an implementation of one embodiment of an OPO system in accordance with the present disclosure;

FIG. **4** is a plot of a gas absorption band and OPO output frequencies;

FIG. **5** is a process flow diagram of an embodiment of a method for operating an OPO system in accordance with the present disclosure;

FIG. **6** is a process flow diagram of an alternative method for operating an OPO system;

FIG. **7** is an isometric view of an embodiment of a DIAL system in accordance with the present disclosure;

FIG. **8** is a schematic block diagram for an embodiment of a DIAL system in accordance with the present disclosure;

FIG. **9** is a process flow diagram of an embodiment of a method for operating a DIAL system in accordance with the present disclosure;

FIG. **10** is a process flow diagram of an embodiment of an alternative method for operating a DIAL system in accordance with the present disclosure;

FIG. **11** is a process flow diagram of an embodiment of another alternative method for operating a DIAL system in accordance with the present disclosure;

FIG. **12** is a schematic block diagram of another embodiment of an OPO operable for generating light in the range from NIR to UV in accordance with the present disclosure, and

FIG. **13** is a schematic block diagram of an OPO operable for generating light in the UV range in accordance with the present disclosure.

DETAILED DESCRIPTION

The present disclosure covers systems, devices, and associated methods for tuning an Optical Parametric Oscillator (OPO). In the following description, numerous specific details are provided for a thorough understanding of specific preferred embodiments. However, those skilled in the art will recognize that embodiments can be practiced without one or more of the specific details, or with other methods, components, materials, etc. In some cases, well-known structures, materials, or operations are not shown or described in detail in order to avoid obscuring aspects of the preferred embodiments. Furthermore, the described features, structures, or characteristics may be combined in any suitable manner in a variety of alternative embodiments. Thus, the following more detailed description of the embodiments of the present invention, as illustrated in some aspects in the drawings, is not intended to limit the scope of the invention, but is merely representative of the various embodiments of the invention.

In this specification and the claims that follow, singular forms such as "a," "an," and "the" include plural forms unless the content clearly dictates otherwise. All ranges disclosed herein include, unless specifically indicated, all endpoints and intermediate values. In addition, "optional" or "optionally" refer, for example, to instances in which subsequently described circumstance may or may not occur, and include instances in which the circumstance occurs and instances in which the circumstance does not occur. The terms "one or more" and "at least one" refer, for example, to instances in which one of the subsequently described circumstances occurs, and to instances in which more than one of the subsequently described circumstances occurs.

Referring to FIG. **1**, an optical parametric oscillator (OPO) system **10** includes a resonant cavity **12** having a non-linear crystal **14** located in an optical path of a laser beam within the resonant cavity **12**. The combination of non-linear crystal **14** and resonant cavity **12** may define an OPO **16**.

A pump laser **18** transmits pulses into the resonant cavity **12**. The pulses have a pulse wavelength and corresponding frequency and are emitted periodically at a pulse rate or pulse repetition frequency. The pulses likewise have a pulse duration that may be less than the inverse of the pulse rate (the pulse period). The OPO **16** may further include a seed laser **20** that transmits a seed beam into the resonant cavity **12**.

A controller **22** embodied as a general-purpose computer, function generator, or application specific circuit may generate signals for powering one or both of the pump laser **18** and seed laser **20**. In some embodiments, a pump seed laser **24** emits a pump seed beam into the pump laser **18** and may also be controlled by the controller **22**.

Referring to FIGS. **1** and **2**, the resonant cavity **12** and non-linear crystal **14** may create through the input of a pump laser **18** both a gain bandwidth **30** and a plurality of cavity modes **32** that are bounded by the gain bandwidth **30**. The gain bandwidth **30** results from properties of the non-linear crystal **14** and the geometry of the resonant cavity **12**. The

gain bandwidth **30** is the range of frequencies or corresponding wavelengths at which light amplification will occur within the non-linear crystal **14** when powered by the pump laser **18**.

The cavity modes **32** represent the frequencies or wavelengths at which standing waves can occur within the resonant cavity **12** and may therefore be significantly amplified. Each of the modes **32** lying within the gain bandwidth **30** may be amplified and present in an output beam of the resonant cavity **12** when only the pump laser **18** is transmitted into the resonant cavity **12**.

The seed laser **20** transmits light into the resonant cavity **12** with a frequency or wavelength within the gain bandwidth **30** and results in selection of one of the modes **32** corresponding to the frequency of the seed laser **20**. Photons of the seed laser beam incident on the non-linear crystal **14** produce additional photons (i.e., greater power than the original seed laser beam) with identical phase, wavelength, and frequency being emitted from the crystal. Accordingly, the seed laser **20** ensures that photons with the seed laser frequency will dominate and reduce the number of photons emitted corresponding to the other modes **32**.

The seed laser **20** may be frequency tunable and therefore can be modulated to select one of the modes **32** and thereby control the output of the resonant cavity **12** within the bounds of the gain bandwidth **30**. For example, the seed laser **20** may provide a beam with a first frequency profile **34** (λ_1) corresponding to one of the frequency modes **32**. The first frequency profile **34** (λ_1) can be obtained by transmitting a seed beam from the seed laser **20**, the seed beam having a center frequency proximate the center frequency of the first frequency profile **34** (λ_1), into the resonant cavity **12**.

By modulating the seed laser **20** to emit a second beam with a second frequency, a second frequency profile **36** (λ_2) with a center frequency at a different mode **32** may be obtained at the output of the resonant cavity **12**. Note that no modification of the resonant cavity **12** or properties of the non-linear crystal **14** is required. Frequency modulation of the output of the OPO **16** may therefore be made by changing the modulation frequency of the seed laser **20** and the relaxation oscillation response of the OPO **16**.

FIG. **3** illustrates an implementation of an OPO system **10**. In the illustrated embodiment, the pump laser **18** may be a laser of type Nd:YAG, Nd:YLF, Tm:YAG, Ho:YAG, Er:YAG, KrF, or the like. In particular, a high power, single mode, Q-switched Nd:YAG, laser injection seeded at 1064 nm, has been found to be workable.

The pump laser **18** typically emits at a wavelength different from that of the output beam **56** of the OPO system **10**. For example, in the illustrated implementation where an Nd:YAG pump laser **18** is used, the pump wavelength may be 1064 nm and the output beam **56** wavelength may be 1.5 μm.

A typical non-linear crystal emits at two wavelengths when excited by a pump laser. The two wavelengths are called the idler beam and signal beam by convention. In the illustrated embodiment, the signal beam is the output and the idler beam has a wavelength of 3.4 μm.

In the illustrated embodiment of FIG. **3**, a dichroic mirror **40** combines a pump beam **42** emitted by the pump laser **18** and a seed beam **44** emitted from the seed laser **20**. The pump beam **42** and seed beam **44** are incident on opposing surfaces of the dichroic mirror **40**, which is oriented at an angle of 45 degrees with respect to each beam **42**, **44**. The dichroic mirror **40** may be highly reflective at the pump laser wavelength and transmissive at the seed laser wavelength.

The resonant cavity **12** may be a ring resonator cavity defined by two dichroic mirrors **46**, **48**, and a turning prism **50**, that establish a rectangular path followed by a circulating beam **52** within the resonant cavity **12**. Tuning prism **50** may also be replaced by two or more dichroic mirrors, as shown in other embodiments. Other resonant cavity configurations known in the art may also be used, including, but not limited to, a linear optical path OPO cavity.

The circulating beam **52** may propagate in the counter clockwise direction such that light transmitted through the mirror **46** is incident on the turning prism **50**, which redirects incident light onto the mirror **48**. The mirror **48** directs incident light onto the mirror **46**, and the cycle continues.

The illustrated resonant cavity **12**, using a turning prism and dichroic mirrors **40**, **46**, and **48**, enables isolation of the pump laser **18** from the resonant cavity without the use of a Faraday isolator. However, other resonant cavities making use of Faraday isolators may also benefit from aspects of the present disclosure.

The dichroic mirror **48** may be highly reflective of the signal beam wavelength, (the desired output) and highly transmissive of other beam wavelengths. For example, a diagnostic beam **58**, including light having the pump and idler wavelengths, may be transmitted through the dichroic mirror **48**. The diagnostic beam **58** may be measured for monitoring purposes.

The dichroic mirror **46** may be partially transmissive at the signal wavelength such that a portion of the circulating beam **52** at the signal wavelength will remain within the resonant cavity **12** and a portion will be emitted through the mirror **46**. Light transmitted through the dichroic mirror **46** may be incident on another dichroic mirror **54** that is tuned to be highly reflective at the signal wavelength. The output beam **56** reflected from the dichroic mirror **54** may therefore include almost exclusively light at the signal wavelength.

Non-linear crystals **14** may be located within the optical path of the circulating beam **52** within the resonant cavity **12**. In the illustrated embodiment, one non-linear crystal **14** is located between the mirror **46** and the turning prism **50** and another between the mirror **48** and the turning prism **50**. In embodiments, four non-linear crystals **14** may be used. For example, each non-linear crystal **14** in FIG. **3** may be replaced by two non-linear crystals **14**. Alternatively, only one non-linear crystal **14** may be used.

The non-linear crystals **14** may include potassium titanyl arsenate (KTA) crystals. The non-linear crystals **14** may also include other nonlinear media known in the art, including, but not limited to, potassium titanyl phosphate (KTP), rubidium titanyl arsenate (RTA), lithium niobate, silver gallium sulphide (AgGaS2), silver gallium selenide (AgGaSe2), zinc germanium diphosphide (ZnGeP2), cadmium selenide (CdSe), potassium dihydrogen phosphate (KDP), Beta barium borate (BBB), lithium boron oxide (LBO), and cesium lithium borate (CLBO).

The non-linear crystals **14** may be non-critical phase matching (NCPM) crystals that allow a large acceptance angle for the pump laser **18**, such as the illustrated pump laser **18** embodied as a single mode pump source. In addition, given the large bandwidth acceptance at NCPM, the seed laser **20** can drive the OPO system **10** to emit at arbitrary injection seeded wavelengths of frequencies across a wide wavelength or frequency band. Note that no mechanical tuning is required to obtain a change in wavelength at the output of the OPO system **10**.

The resonant cavity **12** may be actively stabilized through temperature control or by using a piezo transducer or other line-locking (e.g., dithering) schemes to further enhance the frequency control of the resonant cavity **12**.

In embodiments, the position or orientation of the non-linear crystals **14** in the system may be fixed. The angle of the non-linear crystals may also not change for purposes of tuning the output signal. Likewise, the angle of incidence of the pump beam **42** and seed beam **44**, with respect to the non-linear crystals **14**, may also be fixed.

In some embodiments, the gain bandwidth **30** may be shifted by altering one or more of the orientation, temperature, and pressure of the non-linear crystals **14** or by altering an applied voltage to the non-linear crystals **14**. Modification of the angle of incidence of a pump beam **42** may also be used to shift the gain bandwidth **30**. Shifting may enable access to a different frequency band within which rapid tuning may occur. In embodiments, rapid frequency tuning above the pulse rate or at a modulation frequency above the inverse of the pulse duration is preferably performed by frequency modulation of the seed laser **20**.

The seed laser **20** may be embodied as a laser diode **60** coupled to the resonant cavity **12** by means of a fiber optic cable **62**. However, any laser known in the art that can be rapidly tuned by current or voltage at frequencies comparable to the pulse rate or the inverse of the pulse duration may be used. In embodiments where mechanical means are used to change the gain bandwidth **30**, any laser known in the art may be used, regardless of the laser's ability to be rapidly tuned (or frequency modulated).

A frequency agile 1.5 μm diode laser that produces a narrow linewidth signal wave at 1.533 μm has been found to provide good performance. Laser diodes may be frequency tunable by modulating a drive current and therefore provide a high degree of frequency agility. For example, a laser diode may have a wavelength modulation frequency as large as 10 Hz, 1 kHz, 1 MHz, 1 GHz. For example, the laser diode may have a wavelength modulation frequency between about 10 Hz and about 1 GHz, or between about 1 kHz and about 1 MHz, or between about 1 MHz and about 1 GHz, or between about 1 kHz and about 1 GHz (e.g., 1, 2, 3, 4, 5, 6, 7, 8, 9, or 10 GHz). The laser diode modulation frequency may correspond to the output beam **56** being modulated at the same frequency or frequency range.

The laser diode **60** may have a wavelength modulation frequency, or pulse repetition frequency greater than or equal to the pulse repetition frequency of the pump laser or the inverse of the pulse duration. For example, in the illustrated embodiment, the pump laser **18** may have a pulse rate of 30 Hz with a pulse duration of 10 ns. The laser diode **60** in such an embodiment may have a wavelength modulation frequency that is greater than or equal to about 30 Hz, or greater than or equal to about 100 MHz (1/(10 ns)).

In illustrative experiments, upon interaction with the KTA non-linear crystals **14**, a 1.5 μm signal beam was generated with a bandwidth of approximately 60 GHz. To narrow the bandwidth of the 1.5 μm signal beam, a 1.5 μm seed laser **20** was used to select a mode from this 60 GHz bandwidth. As a result, the bandwidth of the 1.5 μm OPO output went from 60 GHz to about 120 MHz. As described above with respect to FIG. **2**, any mode within the 60 GHz bandwidth could have been selected by tuning the wavelength of the seed laser **20** to the mode.

Referring to FIG. **4**, an OPO system may be used to perform differential absorption light detection and ranging (DIAL). Gases within the atmosphere have an absorption spectrum with multiple bands of high absorption. DIAL may be used to quantify the amount of gas within the atmosphere or within a beam's optical path based on the absorption of light by the gas. Detectable gases may include, for example, aerosols, O_3, CH_4, N_2O, HCN, CO, HDO, HCL, HF, H_2O, or OCS. In FIG. **4**, line **120** represents one absorption band of a gas of interest. In DIAL, gas within a region of interest is irradiated with a beam having a first frequency **122** (λ_1) and the amount of light backscattered is measured. Gas within the region of interest is then irradiated with a beam having a second frequency **124** (λ_2). The amount of light backscattered from the region of interest is again measured.

One of the frequencies, **122** or **124**, is chosen because it lies within the absorption band **120** at a region of high absorption for a particular gas. The other of the frequencies, **122** or **124**, is chosen because it is a frequency at which little absorption occurs for the gas of interest. For example, absorption by a gas present in a beam's optical path (e.g., the atmosphere) at one of the frequencies **122**, **124**, may be 10% to 90% less than the absorption at the other of the frequencies **122**, **124**. In some methods, more than one frequency may be used in the high absorption region and more than one frequency may be used in the low absorption region. For example, one frequency may be 90% and a second 60% less than the absorption at the other end of the frequencies **122**, **124**.

The measurement of backscattered light (e.g. the intensity versus time) at a frequency with little absorption provides a reference for evaluating the measurement of backscattered light at a frequency with high absorption (e.g., frequency **122**). By evaluating these measurements, the concentration of the gas having the given absorption band **120** may be characterized. The measurement and evaluation of measurements of backscattered light may be performed according to any methods for performing DIAL known in the art.

The wavelengths of light achievable using the OPO system **10** may be particularly useful in a DIAL system for measuring various gases. For example, the UV wavelengths achievable using the OPO **10** may be particularly useful for measuring sulfur dioxide (SO_2). Other wavelengths from the UV to NIR may be useful for measuring CO_2, CH_4, NO_s, SO_x, HCN, H_2O, O_3, Benzene, H_2S, Toluene, or other gases. The OPO **10** may be used to generate a modulated output that modulates the wavelength of the output of the OPO at a frequency of high absorption and a frequency of low of absorption for a given gas. The amount of backscattered light responsive to each pulse may then be used to perform DIAL measurements as described above.

FIG. **5** illustrates a method **80** for operating an OPO system, such as the OPO system described above. The method **80** may be executed by an operator, by a controller **22**, or by a combination thereof. The frequencies of the seed laser **20** are identified **82** that are necessary to produce desired output beams **56** with frequencies in regions of high or low absorption for a particular gas. For purposes of this disclosure, frequency and wavelength may be used interchangeably with respect to their description of light. Accordingly, identifying the frequencies **82** of the seed laser **20** light may include identifying **82** the wavelengths of the seed laser light.

In the depicted embodiment, the seed laser **20** and the pump laser **18** are synchronized **84**. Synchronization may result in the seed beam and pump pulse being generated simultaneously or substantially overlapping in time (e.g., greater than 80%, preferably greater than 90%, of the pulse duration). As shown in FIG. **3**, the seed beam and pump pulse are transmitted into the resonant cavity **12**. As described above, the result is an output beam **56** that has a center frequency and wavelength equal to the seed beam **44** frequency and wavelength.

A first drive signal having a current or voltage effective to obtain a first frequency is generated **86**. In embodiments, the seed laser **20** is driven with the control signal to generate **88** a

seed beam having the selected frequency or wavelength. A pump pulse is also generated **90**.

A second drive signal having a current or voltage effective to obtain a second frequency or wavelength may be generated **92**. The seed laser **20** is driven with a drive signal to generate **94** a seed beam having a second frequency or wavelength, and a pump pulse is again generated **96**, substantially overlapping the seed beam in time. The generation steps **86-94** are preferably performed such that the seed laser **20** is emitting at the desired frequency or wavelength by the time the next pulse is generated **96**. That is, immediately following the pulse generated **90** in the previous pulse generation step **90**, a new pulse is generated **96** according to the specified pulse rate of the pump laser **18**. As noted above, this requires modulating the frequency and wavelength of the seed laser **20** at a frequency greater than the pulse rate.

FIG. **6** illustrates an alternative method **100** for operating an OPO system, such as the OPO system **10** described above. The method **100** includes identifying **102** the frequencies or wavelengths and synchronizing **104** the operation of the seed laser **20** and the pump laser **18**. A first drive signal having a controlled voltage, current, or both effective to cause the seed laser **20** to emit at the first frequency or wavelength is generated **106**. The seed laser **20** is driven with the first drive signal to generate **108** a seed beam having a first frequency or wavelength. A pump pulse is generated **110** so as to substantially overlap in time with the seed beam.

A second drive signal having a controlled voltage, current, or both effective to cause the seed laser **20** to emit at a second frequency or wavelength is then generated **112**. The seed laser **20** is driven with the second drive signal to generate **114** a seed beam having the second frequency or wavelength. Steps **108**, **112**, and **114** may be performed repeatedly during generation **110** of a single pump pulse. Steps **108**, **112**, and **114** may be performed in a continuous fashion such that the seed beam sweeps continuously across a range of frequencies during generation **110** of a single pump pulse.

Referring to FIG. **7**, an embodiment of a DIAL system **130** may include a pump laser **18** and an OPO **16** as described above. The OPO **16** includes the seed laser **20** as described above in addition to the resonant cavity **12** and the one or more non-linear crystals **14**. The DIAL system **130** may further include a detector **132** for receiving backscattered light from a region of interest and a controller **134**. The detector **132** may include lenses, for focusing received light, and a light sensor. The detector **132**, pump laser **18**, and OPO **16** may be mounted to orient actuators **136** for rotating the OPO **16** and detector **132** in both the vertical and horizontal planes. The orientation actuators **136** may mount the pump laser **18**, OPO **16**, and detector **132** to a housing **138**. The controller **134** may be mounted within the housing **138**.

Referring to FIG. **8**, the controller **134** may be embodied as a general purpose computer or application-specific computing device. The controller **134** may include a user interface **140** for receiving user instructions and presenting output data. The user interface **140** may include a display screen, keyboard, touch screen, pointing device, or any other data input and output device known in the art.

The controller **134** may further include a frequency selection module **142** that determines at which frequency or wavelength the OPO **16** will emit. The frequency selection module **142** may be instructed to switch between different light frequencies at a switching frequency greater than the pulse rate or greater than the inverse of the pulse duration of the pump laser **18**. The frequency selection module **142** may also be instructed to sweep continuously between the two frequencies. The frequency selection module **142** may simply receive a frequency value specified by the user using the user interface **140**.

The output of the frequency selection module **142** may be input to a seed driver module **144**. The module **144** generates an electrical signal having a voltage and current effective to cause the seed laser **20** to emit at the frequency or wavelength identified by the frequency selection module **142**. The output of the seed driver module **144** is coupled to the seed laser **20**.

The pump driver module **146** generates a drive signal for the pump laser **18**. This may include generating a drive signal for the pump seed laser **24**. The pump driver module **146** may generate a pulsed or continuous drive signal and may simply generate a drive signal in response to a user instruction turning on the pump laser **18**. Where the pump laser **18** has a tunable frequency, amplitude, pulse rate, pulse duration, or combination thereof, the pump driver module **146** may translate instructions, intended to achieve a desired value for these parameters, into the appropriate drive signal.

The controller **134** may also include a measurement module **148** that receives the output of the detector **132**. The measurement module **148** may include any device, software module, or both, known in the art to be capable of measuring back-scattered or reflected light in a DIAL system. The controller **134** may further include an analysis module **150** including any device, software module, or both, known in the art to be capable of analyzing DIAL measurements in order to characterize gas in a region of interest.

Referring to FIG. **9**, a DIAL system, such as the DIAL system **130**, may be used to perform the illustrated method **160**. A first frequency or wavelength is selected **162**. The first frequency may be a high absorption frequency for a gas of interest, e.g., a frequency at which the gas of interest has an absorption within about 10% of its peak absorption for the absorption band containing the first frequency. The first frequency may also be a low absorption frequency, for example, a frequency at which the gas of interest has an absorption substantially less, (e.g., less than about 90% of the peak) absorption for the absorption band closest to the first frequency.

A drive signal for the seed laser **20** is then generated **164** effective to cause the seed laser **20** to emit the frequency previously selected **162**. The seed laser **20** is driven with the drive signal to generate **166** a seed beam having the first frequency. A pump pulse is also generated **168** such that the pump pulse overlaps substantially in time with the seed beam generated at step **166**. The output of an OPO is then transmitted **170** toward a region of interest. Light backscattered from the region of interest is then measured **172**.

A second frequency or wavelength is selected **174**, and a corresponding drive signal is generated **176**, followed by generation **178** of a seed beam having the second frequency. The second frequency may have an absorption for the gas of interest that is less than or equal to about 10% that of the first frequency. The order may be reversed and the first frequency may have an absorption for the gas of interest that is less than or equal to about 10% of that of the second frequency. A pump pulse is also again generated **180** such that the second pulse overlaps substantially in time with the seed beam generated at step **178**. The output of the OPO **16** is then again transmitted **182** toward the region of interest. Again, light reflected from the region of interest is then measured **184**.

The measurements taken at steps **172** and **184** are then analyzed **186** to characterize the concentration of the gas of interest in the region of interest according to methods known in the art of DIAL analysis. Data characterizing the gas of

interest within the region of interest may then be output **188** in a human or computer readable form.

Referring to FIG. **10**, in an alternative embodiment, a method **200** may be identical to other methods, with the exception of generating **168** the pump pulse and transmitting **170** the output of the OPO **16**. Due to the novel tuning methods disclosed herein, modulation of the output frequency of the OPO **16** may be faster than the pulse rate or the inverse of the pulse duration. Accordingly, generating **168** the pump pulse and transmitting **170** the output of the OPO **16**, may substantially overlap in time both generating **166** the seed beam at the first frequency and generating **178** the seed beam at the second frequency, such that the second pulse generation step **180** and second transmitting step **182** may be omitted.

Accordingly, the output **56** of the OPO **16** corresponding to a single pump pulse will include portions at the first frequency and at the second frequency. Measuring **172** backscattered light and measuring **184** the backscattered light may occur at appropriate times to measure the portion of reflected light corresponding to portions of the OPO output **56** corresponding to the first and second frequencies, respectively.

FIG. **11** illustrates an alternative method **210** for performing DIAL analysis. In the method **210**, a frequency or wavelength range is first selected **212**. The frequency range may include frequencies of both high absorption and low absorption for the gas of interest. For example, the frequency range may include first and second frequencies such that absorption at one of the frequencies is less than 10% of that of the other frequency. One of the first and second frequencies may have an absorption that is within 90% of the peak absorption of the absorption band of the gas of interest closest to that frequency.

A drive signal progression is generated **214** that will cause the seed laser **20** to sweep through the frequency range that was selected **212**. In response to the drive signal, the seed laser **20** will generate **216** a seed beam **44** that sweeps through the selected frequency range. While the seed beam **44** is being generated **216**, a pump pulse is also generated **218** using the pump laser **18**. The pump pulse preferably substantially overlaps in time the generation **216** of the seed beam.

As a result of generation **216** of the seed beam and generation **218** of the pump pulse, an output beam is transmitted **220** to a region of interest. Light backscattered from the region of interest is repeatedly measured **222**. The measurements are then analyzed **224** to determine the absorption at various frequencies within the frequency range that was selected **212**. Thus one may characterize the concentration of the gas of interest in the region of interest. Data characterizing the gas of interest within the region of interest may then be output **226** in a human or computer readable form.

Referring to FIG. **12**, another embodiment of an OPO **230** may be suitable for use in accordance with any of the methods and systems described above. The illustrated OPO **230** is particularly useful for generating output beams within the ultraviolet (UV) to the near infrared (NIR) range. The OPO **230** may include two or more seed lasers **232***a* and **232***b*. As for other embodiments discussed herein, the seed lasers **232***a* and **232***b* may be embodied as laser diodes, such as distributed feedback laser diodes. In other embodiments, more than two seed lasers may be used, for example, 3, 4, or more seed lasers may be used. The seed lasers may be formed into an array of seed lasers or the seed lasers may form part of an interchangeable module containing one or more seed lasers capable of operating at different frequencies. Similar to the embodiments described above with respect to seed laser **232**, seed lasers **232***a* and **232***b* may be driven by one or more controllers (not shown) and may be modulated to emit beams with different frequencies

The seed lasers **232***a* and **232***b* may emit beams into a coupler, such as a fiber coupler **234**, that combines the beams into a combined beam **236**. The combined beam **236** may then be input into a resonant cavity **238** having one or more non-linear crystals **240** in the optical path thereof.

In some embodiments, the resonant cavity **238** may be actively stabilized through temperature control or by using a piezo transducer or other line-locking (e.g., dithering) schemes to further enhance the frequency control of the resonant cavity **12**. The one or more non-linear crystals **240** may have various attributes including the angle of the crystal or the angle of incidence of the pump beam, or the temperature, pressure or applied voltage on the crystal. In the illustrated embodiment, the non-linear crystals **240** may include Beta barium borate (BBO). However, other non-linear crystals may also be used.

A pump laser **242** may emit a pump beam **244** which is input to the resonant cavity **238**. The pump laser **242** may include any type of laser described herein as being suitable for operation as a pump laser. The pump laser may include two or more pump lasers with beams combined through a fiber coupler (not shown). Like the seed lasers, the pump laser may be part of an interchangeable module containing one or more pump lasers capable of operating at different frequencies.

The pump beam **244** may be combined with the combined beam **236** output from the fiber coupler **234**, such as by means of a dichroic mirror **246** or other means for combining beams. The dichroic mirror **246** may be highly reflective at the pump beam wavelength and highly transmissive at the seed beams' wavelengths. The pump beam **244** and combined beam **236** may then be input to the resonant cavity **238**.

In response to the pump beam **244**, the one or more non-linear crystals **240** output a signal beam **248** and an idler beam **250**. In practice, the signal beam has a wavelength that is to be used in further stages and represents the desired output of the non-linear crystal **240**. The idler beam **250** may be ignored or used to monitor intensity or other parameters.

A dichroic mirror **252** or other structure defining the cavity may emit an output beam **254** from the resonant cavity. The output beam **254** may include some of the signal beam **248** emitted from the non-linear crystals **240**. The output beam **254** may be received by a summing element **256**. The summing element **256** also receives a portion of the pump beam **244**. This may be accomplished by means of a high reflector for both pump and signal at **260***a*. Upon receiving a portion of the pump beam **244** and a portion of the signal beam **248**, the summing element **256** generates an output beam **258**, which may be a light beam in the UV to NIR range. The summing element **256** may be embodied as a sum frequency generator.

In some embodiments, the summing element **256** may be embodied as a non-linear crystal, critically phase-matched to be effective to operate as a sum frequency generator (SFG). The summing element **256** may be a non-linear crystal having some or all of the attributes of non-linear crystals discussed above. For example, a non-linear crystal may be bi-axial or uniaxial, or may be frequency tuned through mechanical (e.g., movement, rotation), temperature, or electrical means. In embodiments, the SFG is implemented using Beta barium borate.

The OPO **230** may include additional structures to direct beams and define the cavity **238**. For example, the cavity may be defined by three or more mirrors **260***a*-**260***c*, in addition to the dichroic mirror **252**. One or more of the mirrors **260***a*-**260***c*, such as the mirrors **260***a*, **260***c* may also be dichroic mirrors having a frequency response effective to transmit the idler beam wavelength but reflect the signal beam wavelength. In the illustrated embodiments, a mirror **262** directs

the combined beam **236** into the dichroic **246** and a mirror **264** directs the pump beam **244** into the dichroic mirror **246**. Other mirrors and optical components may also be used to direct beams and define the resonant cavity **238**.

As noted above, two seed lasers **232***a*-**232***b* are positioned to emit seed beams into the resonant cavity. The seed beams **232***a*-**232***b* may have different wavelengths and different intensities. The separation between the two seed wavelengths may be broader than the gain bandwidth of the non-linear crystals **240** at one, static phase-matching angle. Accordingly, one or both of the non-linear crystals **240** may be mounted or otherwise coupled to an actuator **266** operable to change the angle of the crystal **240** relative to the propagation direction of beams passing through. The change in angle may be in the plane of the diagram of FIG. **12** or out of the plane.

The summing element **256** may likewise be mounted or otherwise coupled to an actuator **268** that is operable to adjust the angle of the summing element **256** relative to the output beam **254**. Accordingly, the change in angle may be used to shift the wavelength band in which the summing element **256** is operable to perform this function. The change in angle may be in the plane of the diagram of FIG. **12** or out of this plane. The actuators **266**, **268** may be coupled to a controller (not shown) or other component operable to generate an oscillating signal. The controller or other actuator may be programmed to drive the actuators **266**, **268** in a manner to select one of the two seed wavelengths for the signal beam **248**. The actuators **266**, **268** may be implemented using a compliant actuator, such as a piezoelectric actuator.

As noted above, the seed beams are operable to select one of the lasing modes of the resonant cavity. In the embodiment of FIG. **12**, actuation of the non-linear crystals **240** is performed to be effective to select which of the two seed beam wavelengths is followed by the signal beam **248**. Likewise, actuation of the summing element **256** may be performed effective to alter the angle of the summing element **256** such that the summing element **256** performs summing of a portion of the pump beam **244** and a portion of the signal beam **248** having the seed beam wavelength.

The illustrated configuration is operable to achieve relatively broadband operation. For example, the output of the summing element **256** may be a UV beam that is modulated between wavelengths separated by greater than 0.5 nm.

In one example of FIG. **12**, the seed lasers **232***a*-**232***b* were implemented using two DFB laser diodes tuned to wavelengths of 868.5 and 879.3 nm, respectively. The pump laser **242** was implemented using a 355 nm single longitudinal mode (SLM) yttrium aluminum garnet (YAG) laser. In this configuration, the output of the summing element **256** was a UV beam modulated between 252.9 and 252 nm. The illustrated setup is further capable of achieving a tuning range of from about 250.5 to about 254.5 nm.

The output of the OPO **230** may be used to perform LIDAR and DIAL measurements according to some or all of the methods described herein. The UV wavelengths achievable using the OPO **230** may be particularly useful for measuring sulfur dioxide (SO_2). Other wavelengths from UV to NIR may be useful for measuring CO_2, CH_4, NO_x, SO_x, HCN, H_2O, O_3, Benzene, H_2S, or Toluene. The OPO **230** may be used to generate a modulated output that modulates the wavelength of the output of the OPO at a frequency greater than or equal to a pulse frequency of the pump laser **242**. Backscattered light responsive to each pulse may then be used to perform DIAL measurements as described above.

Alternatively, the wavelength of the output of the OPO **230** may be modulated and measurements made faster than an inverse of the pulse duration of pulses output from the pump laser **242**. This may enable inter-pulse measurements as described above with respect to FIGS. **10** and **11**.

Referring to FIG. **13**, an alternative embodiment of an OPO **290** may be suitable for operation in the UV range. The OPO **290** may include a controller **292** that controls a seed laser **232**, such as by controlling an amount of current supplied to the seed laser **232**. As for other embodiments disclosed herein, the seed laser **232** may be a laser diode, such as a distributed feedback laser diode. The seed laser **232** generates a seed beam **294** that is input to the resonant cavity **238** along with the pump beam **244**. Similar to the embodiment of FIG. **12**, the pump beam **244** and seed beam **236** circulate in the resonant cavity **238** and are transmitted through one or more non-linear crystals **240**, which results in a signal beam **248** and an idler beam **250**.

Similar to the embodiment of FIG. **12**, a summing element **256** receives a portion of the pump beam **244** as well as a portion of the signal beam **248**. The summing element **256** is operable to convert the received portions of the pump beam **244** and signal beam **248** into a UV beam **258**. In contrast to the embodiment of FIG. **12**, both the non-linear crystals **240** and summing element **256** may be fixed relative to the resonant cavity **238**. The position and orientation of the non-linear crystals **240** and summing element **256** may be adjustable relative to the resonant cavity **238** during setup or calibration but may remain fixed during operation. Accordingly, the actuators **266**, **268** may be omitted or unused during operation.

Similar to the embodiment of FIG. **12**, the summing element **256** may be embodied as a sum frequency generator (SFG) **256**. Both the summing element **256** and the non-linear crystals **240** may be embodied as any of the materials noted herein as suitable for operation as non-linear crystals. In some embodiments, both the summing element **256** and non-linear crystals **240** are embodied as Beta barium borate (BBO). As for the embodiment of FIG. **12**, the non-linear crystals and the SFG **256** are critically phase matched. However, one phase-matching angle is used in the operation of the device.

In the embodiment of FIG. **13**, the seed laser beam **294** selects a lasing wavelength from the lasing modes of the resonant cavity **238**. Modulation of the seed laser wavelength results in modulation of the signal wavelength. As for other embodiments disclosed herein, the signal wavelength may be substantially equal to the seed laser wavelength.

The summing element **256** may have an acceptance band at which the summing element **256** is capable of functioning as a summing element **256**. Accordingly, modulation of the seed laser wavelength may be constrained to maintain the signal wavelength within this acceptance band. Likewise, modulation of the seed laser wavelength may be constrained to lie within the band of lasing wavelengths at which the combination of the resonant cavity **238** and non-linear crystals **240** is capable of generating a signal beam **248** in response to the pump beam **244**.

In one exemplary setup, a seed laser **232** was implemented using an 845 nm DFB laser diode and the pump laser **242** was implemented using a 355 nm SLM YAG laser. Using these components, a 250 nm UV output beam **258** was obtained with narrow linewidth. Modulation of up to about 0.5 nm was obtained. Using the embodiment of FIG. **13**, UV beam wavelength modulation bandwidth may be achieved up to 0.5 nm. For example, the UV beam wavelength may be modulated in a band from about 0.3 and to about 0.5 nm in response to modulation of the seed laser wavelength. In response to the seed laser modulation, a UV beam emitted by the OPO **290** may be modulated at a frequency as large as 1 kHz, 1 MHz, or 1 GHz (e.g., 1, 2, 3, 4, 5, 6, 7, 8, 9, or 10 GHz).

The output of the OPO **290** may be used to perform Light Detection And Ranging (LIDAR) and Differential Absorption LIDAR (DIAL) measurements according to some or all of the methods described herein. The UV wavelengths achievable using the OPO **290** may be particularly useful for measuring sulfur dioxide (SO_2). Other wavelengths achievable through OPO **290** may be useful for measuring CO_2, CH_4, NO_R, SO_x, HCN, H_2O, O_3, Benzene, H_2S, or Toluene. The OPO **290** may be used to generate a modulated output that modulates the wavelength of the output of the OPO at a frequency greater than or equal to a pulse frequency of the pump laser **242**. Backscattered light responsive to each pulse may then be used to perform DIAL measurements as described hereinabove.

Alternatively, the wavelength of the output of the OPO **290** may be modulated and measurements made faster than an inverse of the pulse duration of pulses output from the pump laser **242**. This may enable inter-pulse measurements as described above with respect to FIGS. **10** and **11**.

Embodiments of the present disclosure may be embodied in other specific forms without departing from its spirit or essential characteristics. The described embodiments are to be considered in all respects only as illustrative, and not restrictive. The scope of the invention is, therefore, indicated by the appended claims, rather than by the foregoing description. All changes which come within the meaning and range of equivalency of the claims are to be embraced within their scope.

It will be appreciated that various of the above-disclosed and other features and functions, or alternatives thereof, may be desirably combined into many other different systems or applications. Also, various presently unforeseen or unanticipated alternatives, modifications, variations or improvements therein may be subsequently made by those skilled in the art, and are also intended to be encompassed by the following claims.

What is claimed is:

1. A laser system comprising:

a pump laser configured to generate a pump beam having a pump wavelength and a pulse repetition frequency (PRF);

a resonant cavity positioned to receive a first portion of the pump beam;

a non-linear crystal positioned within the resonant cavity such that the non-linear crystal and resonant cavity have a band of lasing wavelengths including wavelengths other than the pump wavelength, the non-linear crystal operable to output a signal beam in response to the first portion of the pump beam;

a seed laser positioned to emit a seed signal into the resonant cavity, the seed signal having a seed wavelength and the seed wavelength being within the band of lasing wavelengths;

a seed laser controller electrically coupled to the seed laser and programmed to modulate the seed wavelength at the PRF of the pump laser; and

a sum frequency generator (SFG) positioned to receive a second portion of the pump beam and a portion of the signal beam, the SFG operable to output an output beam in response to the second portion of the pump beam and the portion of the signal beam

an SFG actuator controller electrically coupled to an SFG actuator the SFG actuator controller programmed to modulate the output beam by driving the SFG actuator;

wherein the output beam is an ultraviolet (UV) beam with a wavelength that is modulated in a band from about 0.5 to about 4 nanometers.

2. The laser system of claim **1**, wherein the output beam can be modulated at a frequency between about 10 Hz and about 1 GHz.

3. The laser system of claim **1**, wherein the output beam is an ultraviolet (UV) beam with a wavelength that is modulated in a band from about 0.3 to about 0.5 nm.

4. The laser system of claim **1**, wherein the non-linear crystal is fixed relative to the resonant cavity.

5. The laser system of claim **1**, wherein the seed laser comprises a first seed laser configured to emit a first seed signal having a first seed wavelength and a second seed laser configured to emit a second seed signal having a second seed wavelength, both the first and second seed lasers positioned to emit their respective signals into the resonant cavity, and both the first and second seed wavelengths being within the band of lasing wavelengths.

6. The laser system of claim **5**, further comprising a crystal actuator controller electrically coupled to the crystal actuator, the crystal actuator controller programmed to modulate the output beam by driving the crystal actuator.

7. The laser system of claim **1**, further comprising a crystal actuator coupled to the non-linear crystal.

8. A method for operating a laser comprising:

generating a pump beam at a pump wavelength and a pump pulse repetition frequency (PRF);

transmitting a first portion of the pump beam into a resonant cavity having a non-linear crystal in an optical path thereof, the non-linear crystal operable to emit a signal beam in a band of lasing wavelengths that includes wavelengths different from the pump wavelength;

generating a seed beam having a seed wavelength lying within the band of lasing wavelengths;

modulating the seed wavelength at a frequency greater than or equal to the pump PRF;

transmitting the seed beam into the resonant cavity;

transmitting a portion of the signal beam and a second portion of the pump beam into a sum frequency generator (SFG);

modulating with an SFG actuator an output beam; and

outputting the output beam from the SFG in a band from about 0.5 to about 4 nanometers.

9. The method of claim **8**, wherein modulating the seed wavelength causes a corresponding modulation of an output wavelength of the output beam.

10. The method of claim **8**, wherein the output beam is a UV beam and modulating the seed wavelength causes a corresponding modulation of the UV beam in a band between about 0.3 and 0.5 nanometers wide.

11. The method of claim **8**, wherein:

generating the seed beam comprises activating a laser diode; and

modulating the seed wavelength comprises modulating current supplied to the laser diode.

12. The method of claim **8**, wherein the output beam can be modulated at a frequency between about 10 Hz and about 1 GHz.

13. A method for operating a laser comprising:

generating a pump beam with a pump beam wavelength at a pump pulse repetition frequency (PRF);

transmitting the pump beam into a resonant cavity having a non-linear crystal in an optical path thereof, the non-linear crystal being operable to emit a signal beam in a band of lasing wavelengths that includes wavelengths different from the pump beam wavelength;

generating a first seed beam having a first seed wavelength lying within the band of lasing wavelengths;

generating a second seed beam having a second seed wavelength lying within the band of lasing wavelengths, the second seed wavelength being different from the first seed wavelength;

transmitting the first and second seed beams into the resonant cavity;

transmitting a portion of the signal beam and a portion of the pump beam into a sum frequency generator (SFG);

outputting an output beam having an output beam wavelength from the SFG; and

modulating the output beam wavelength by actuating the non-linear crystal.

14. The method of claim **13**, wherein modulating the output beam wavelength comprises actuating the non-linear crystal effectively to modulate the output beam wavelength at a frequency greater than or equal to the pump PRF.

15. The method of claim **13**, wherein actuating the non-linear crystal comprises actuating the non-linear crystal effective to modulate the signal beam between the first seed wavelength and the second seed wavelength.

16. The method of claim **15**, further comprising actuating the SFG in correspondence with actuation of the non-linear crystal.

17. The method of claim **16**, wherein the output beam is a UV beam and actuating the non-linear crystal comprises actuating the non-linear crystal effective to modulate the wavelength of the UV beam over a range from about 0.5 to about 4 nanometers.

18. A gas characterization system comprising:

a pump laser configured to generate a pump beam having a pump wavelength at a pulse repetition frequency (PRF);

a resonant cavity positioned to receive a first portion of the pump beam;

a non-linear crystal positioned within the resonant cavity such that the non-linear crystal and resonant cavity have a band of lasing wavelengths including wavelengths other than the pump wavelength, the non-linear crystal operable to output a signal beam in response to the pump beam;

a seed laser positioned to emit a seed signal into the resonant cavity, the seed signal having a seed wavelength being within the band of lasing wavelengths;

a seed laser controller electrically coupled to the seed laser and programmed to modulate the seed wavelength at a frequency at least as great as the PRF;

a sum frequency generator (SFG) positioned to receive a second portion of the pump beam and a portion of the signal beam, the SFG operable to output an output beam in response to the second portion of the pump beam and the portion of the signal beam;

an SFG actuator controller electrically coupled to an SFG actuator the SFG actuator controller programmed to modulate the output beam by driving the SFG actuator;

wherein the output beam is an ultraviolet (UV) beam with a wavelength that is modulated in a band from about 0.5 to about 4 nanometers;

a detector configured for receiving a reflected portion of the output beam from a region of interest;

a measurement module configured to receive an output from the detector and produce a measurement of the reflected portion of the output beam; and

an analysis module configured to analyze the measurement from the measurement module and characterize a gas in the region of interest.

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