ALIGNMENT OF LASING WAVELENGTH WITH WAVELENGTH CONVERSION PEAK USING MODULATED WAVELENGTH CONTROL SIGNAL

According to one embodiment of the present invention, a programmable light source comprises one or more semiconductor lasers, a wavelength conversion device, and a laser controller. The controller is programmed to operate the semiconductor laser using a modulated feedback control signal. The wavelength control signal is adjusted based on the results of a comparison of a detected intensity signal with a feedback signal to align the lasing wavelength with the conversion efficiency peak of the wavelength conversion device. Laser controllers and projections systems operating according to the control concepts of the present invention are also provided.
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CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Patent Application Serial Nos. 60/928,725, filed May 11, 2007, for WAVELENGTH CONTROL IN WAVELENGTH SELECTIVE, PHASE, AND GAIN REGIONS OF SEMICONDUCTOR LASERS and 11/894,846 filed August 22, 2007 for ALIGNMENT OF LASING WAVELENGTH WITH WAVELENGTH CONVERSION PEAK USING MODULATED WAVELENGTH CONTROL.

SUMMARY OF THE INVENTION

[0002] The present invention relates generally to semiconductor lasers, laser controllers, laser projection systems, and other optical systems incorporating semiconductor lasers. More particularly, by way of illustration and not limitation, embodiments of the present invention relate generally to methods of aligning the lasing wavelength of a semiconductor laser with the conversion peak of the wavelength conversion device that is optically coupled to the output of the laser.

[0003] For example, short wavelength sources can be configured for high-speed modulation by combining a single-wavelength semiconductor laser, such as a distributed feedback (DFB) laser, a distributed Bragg reflector (DBR) laser, or a Fabry-Perot laser with a wavelength conversion device, such as a second harmonic generation (SHG) crystal. The SHG crystal can be configured to generate higher harmonic waves of the fundamental laser signal by tuning, for example, a 1060nm DFB or DFB laser to the spectral center of an SHG crystal, which converts the wavelength to 530nm. However, the wavelength conversion efficiency of an SHG crystal, such as MgO-doped periodically poled lithium niobate (PPLN), is strongly dependent on the wavelength matching between the laser diode and the SHG device. As will be appreciated by those familiar with laser design, SHG crystals use second harmonic generation properties of non-linear crystals to frequency-double laser radiation directed into the crystal. DFB lasers are resonant-cavity lasers using grids or similar structures etched into the semiconductor material as a reflective medium. DBR lasers are
lasers in which the etched grating is physically separated from the electronic pumping area of
the semiconductor laser.

[0004] The bandwidth of a PPLN SHG device is often very small - for a typical PPLN
SHG wavelength conversion device, the full width half maximum (FWHM) wavelength
conversion bandwidth is often only in the 0.16 to 0.2 nm range and mostly depends on the
length of the crystal. Mode hopping and uncontrolled large wavelength variations within the
laser cavity due to change of the drive current can cause the output wavelength of a
semiconductor laser to move outside of this allowable bandwidth during operation. Once the
semiconductor laser wavelength deviates outside the wavelength conversion bandwidth of the
PPLN SHG device, the output power of the conversion device at the target wavelength drops
dramatically. For example, the DBR section temperature is affected by the amplitude of the
gain-section drive current due to the thermal-crosstalk effect. There are other factors that
make the DBR laser wavelength different from the PPLN wavelength, including variation of
the ambient temperature and manufacturing tolerance of a DBR laser and a PPLN. hi laser
projection systems using a light source consisting of a DBR laser and a PPLN, for example,
the wavelength mismatch between a DBR laser and a PPLN is particularly problematic
because it can generate unintentional changes in power that will be readily visible as defects
at specific locations in the image. These visible defects typically manifest themselves as
organized, patterned image defects across the image because the generated image is simply
the signature of the temperature crosstalk from the gain section to the DBR section.

[0005] Given the challenges associated with wavelength matching and stabilization in
developing semiconductor laser sources, the present inventors have recognized beneficial
means for controlling the wavelength of the semiconductor laser to maintain proper alignment
of the lasing wavelength with the wavelength conversion peak of the wavelength conversion
device. For example, and not by way of limitation, laser controllers programmed to operate
semiconductor lasers according to the concepts of the present invention are contemplated - as
are light sources and laser projection systems driven by such controllers. Although the
concepts of the present invention are described primarily in the context of image forming and
laser projection, it is contemplated that various concepts of the present invention may also be
applicable to any laser application where repeatable low frequency fluctuation of the laser
wavelength is an issue.
BRIEF DESCRIPTION OF THE DRAWINGS

[0006] The following detailed description of specific embodiments of the present invention can be best understood when read in conjunction with the following drawings, where like structure is indicated with like reference numerals and in which:

[0007] Fig. 1 is a schematic illustration of a DBR or similar type semiconductor laser optically coupled to a light wavelength conversion device;

[0008] Fig. 2 is a schematic illustration of a laser projection system according to one embodiment of the present invention;

[0009] Fig. 3 illustrates an example of a conversion efficiency curve for an SHG crystal;

[0010] Fig. 4 illustrates the evolution of optimum and actual DBR voltage under increasing gain current in a semiconductor laser;

[0011] Fig. 5 is a schematic illustration of a programmable light source according to one embodiment of the present invention;

[0012] Fig. 6 is a schematic illustration of the manner in which a programmable controller according to one embodiment of the present invention can be configured; and

[0013] Fig. 7 is a flow chart illustrating processes according to specific embodiments of the present invention.

DETAILED DESCRIPTION

[0014] Although the specific structure of the various types of semiconductor lasers in which the concepts of particular embodiments of the present invention can be incorporated is taught in readily available technical literature relating to the design and fabrication of semiconductor lasers, the concepts of particular embodiments of the present invention may be conveniently illustrated with general reference to a three-section DBR-type semiconductor laser 10 illustrated schematically in Fig. 1. In Fig. 1, the DBR laser 10 is optically coupled to a light wavelength conversion device 20. The light beam emitted by the semiconductor laser 10 can be either directly coupled into the waveguide of the wavelength conversion device 20 or can be coupled through collimating and focusing optics or some other type of suitable optical element or optical system. The wavelength conversion device 20 converts the incident light into higher harmonic waves and outputs the converted signal. This type of configuration is particularly useful in generating shorter wavelength laser beams from longer wavelength
semiconductor lasers and can be used, for example, as a visible laser source for laser projection systems.

[0015] Although the concepts of the present invention are described primarily in the context of DBR lasers, it is contemplated that the control schemes discussed herein will also have utility in a variety of types of semiconductor lasers, including but not limited to DFB lasers, Fabry-Perot lasers, and many types of external cavity lasers.

[0016] The DBR laser 10 illustrated schematically in Fig. 1 comprises a wavelength selective section 12, a phase matching section 14, and a gain section 16. The wavelength selective section 12, which can also be referred to as the DBR section of the laser 10, typically comprises a first order or second order Bragg grating positioned outside the active region of the laser cavity. This section provides wavelength selection, as the grating acts as a mirror whose reflection coefficient depends on the wavelength. The gain section 16 of the DBR laser 10 provides the major optical gain of the laser and the phase matching section 14 creates an adjustable phase shift between the gain material of the gain section 16 and the reflective material of the wavelength selective section 12. The wavelength selective section 12 may be provided in a number of suitable alternative configurations that may or may not employ a Bragg grating.

[0017] Respective control electrodes 2, 4, 6 are incorporated in the wavelength selective section 12, the phase matching section 14, the gain section 16, or combinations thereof, and are merely illustrated schematically in Fig. 1. It is contemplated that the electrodes 2, 4, 6 may take a variety of forms. For example, the control electrodes 2, 4, 6 are illustrated in Fig. 1 as respective electrode pairs but it is contemplated that single electrode elements 2, 4, 6 in one or more of the sections 12, 14, 16 will also be suitable for practicing particular embodiments of the present invention. The control electrodes 2, 4, 6 can be used to inject electrical current into the corresponding sections 12, 14, 16 of the laser 10. For example, the injected current can be used to alter the operating properties of the laser by controlling the temperature of one or more of the laser sections, injecting electrical current into a conductively doped semiconductor region defined in the laser substrate, controlling the index of refraction of the wavelength selective 12 and phase matching 14 sections of the laser 10, controlling optical gain in the gain section 16 of the laser, etc.

[0018] The wavelength conversion efficiency %I of the wavelength conversion device 20 illustrated in Fig. 1 is dependent on the wavelength matching between the output of the semiconductor laser 10 and the wavelength conversion efficiency curve of the wavelength.
conversion device 20. In cases where the wavelength conversion device 20 comprises an
SHG crystal, the output power of the higher harmonic light wave generated in the SHG
crystal 20 drops drastically when the output wavelength of the laser 10 deviates from the peak
of the conversion efficiency curve of the SHG crystal. An example of a conversion efficiency
curve for an SHG crystal is illustrated in Fig. 3. The peak of the conversion efficiency curve
is positioned at about 1060 nm. Generally, the output power of the higher harmonic light
wave generated in the SHG crystal 20 drops as the lasing wavelength drifts from this value.
Accordingly, the lasing wavelength should be maintained as close as possible to the peak of
the conversion efficiency curve (1060 nm) to operate at maximum efficiency.

[0019] However, a number of factors can affect the value of the lasing wavelength. For
example, when the semiconductor laser 10 is modulated to produce data, the thermal load in
the laser varies. The resulting change in laser temperature changes the lasing wavelength,
creating a variation of the efficiency of the SHG crystal 20. In the case of a 12 mm-long
PPLN SHG device, a temperature change in the semiconductor laser 10 of about 2°C will
typically be enough to take the output wavelength of the laser 10 outside of the 0.16 nm full
width half maximum (FWHM) wavelength conversion bandwidth of the SHG crystal 20.

[0020] In addition, the present inventors have recognized that semiconductor lasers are
commonly subject to wavelength drift and associated cavity mode hopping. More
specifically, when the injection current applied to the gain section 16 increases, the
temperature of the gain section also increases. As a consequence, the cavity modes move
towards higher wavelengths. The wavelength of the cavity modes move faster than the
wavelength of the DBR section so the laser reaches a point where a cavity mode of lower
wavelength is closer to the maximum of the DBR reflectivity curve. At that point, the mode
of lower wavelength has lower loss than the mode that is established and, according to basic
principles of laser physics, the laser then automatically jumps to the mode that has lower loss.
The wavelength slowly increases and includes sudden mode hops whose amplitude is equal to
one free spectral range of the laser cavity. This behavior is illustrated in detail in the
commonly assigned, copending U.S. patent applications noted above, the disclosures of
which are incorporated herein by reference. The present inventors have also recognized that
semiconductor lasers commonly exhibit a temperature evolution signature that can create
unfavorable patterning in the output of the laser and the output of a wavelength conversion
device coupled to the laser.
Although the present invention is not limited to any particular manifestation of the wavelength variations described herein, if these phenomena occur in a laser projection system, an example of which is illustrated schematically in Fig. 2, these wavelength fluctuations can create intensity variations and noise in the projected image that would be readily visible to the human eye. According to one embodiment of the present invention, a programmable light source is introduced to address this problem. Referring to Fig. 5, the light source 100 comprises at least one semiconductor laser 110, a wavelength conversion device 120, and a laser controller 130 programmed to operate the semiconductor laser 110. Typically, as is noted above, the laser 110 will comprise a wavelength selective section, a gain section, etc. The output of the semiconductor laser 110 is coupled to the input of the wavelength conversion device 120, and the laser controller is programmed to execute or direct execution of steps or acts according to the present invention.

Specifically, in accordance with one embodiment of the present invention, the laser controller 130 is programmed to control the periodic lasing intensity of the semiconductor laser 110 by controlling the injection of gain current $I_g$ into the gain section of the semiconductor laser 110. Typically, the periodic frequency $f_{DATA}$ of the gain current $I_g$ represents a video image or some other type of encoded data signal.

The controller 130 is also programmed to control the lasing wavelength $\lambda_i$ of the semiconductor laser 110 by using a wavelength control signal to control the index of refraction of the wavelength selective section, subsequently by controlling the temperature $T_X$ vis-a-vis a thermal effect, or the carrier density via a carrier effect or the electrical field via a electro-optical effect. The thermal effect can be conveniently realized by a heater current in electrically resistive heating elements thermally coupled to the wavelength selective section of the semiconductor laser 110 or a injection current into the DBR wavelength selective section. Alternatively, the carrier effect can be realized by an injection current in the wavelength selective section of the semiconductor laser 110. In addition, an electro-optical effect can be introduced by the voltage bias applied to the wavelength selective section.

Given the aforementioned ability to control the lasing wavelength $\lambda_i$, it is further noted that the controller 130 can be programmed to direct modulation the lasing wavelength $\lambda_i$ by using one or more of the above-noted wavelength control mechanisms to create a modulated feedback control signal. According to this aspect of the present invention, the periodic frequency $f_{MOD}$ of the modulated feedback control signal, as manifested in the
modulated output intensity \( I(2V_{MOD}) \) of the wavelength conversion device 120, is substantially different than the periodic frequency \( V_{DATA} \) of the data signal, as established in controlling the gain current \( I_g \) and as manifested in the data signal output intensity \( I(2V_{DATA}) \) of the wavelength conversion device 120. For the convenience of illustration, the modulated output intensity \( I(V_{MOD}) \) and the data signal output intensity \( I(V_{DATA}) \) of the wavelength conversion device 120 are illustrated in Fig. 5 by referring to \( I(2V_{MOD}) \) and \( I(2V_{DATA}) \) because many applications of the present invention will utilize a frequency-doubling SHG crystal as the wavelength conversion device 120.

[0025] Given the two distinct portions of the output signal of the wavelength conversion device 120, the controller can be further programmed to determine whether the lasing wavelength \( \lambda_i \) is shorter or longer than the conversion efficiency peak of the wavelength conversion device 120, an example of which is illustrated in Fig. 3. To do so, the controller 130 can be programmed to compare the modulated output intensity \( I(2V_{MOD}) \) with the modulated feedback control signal and adjust the wavelength control signal to increase the lasing wavelength \( \lambda_i \) when the comparison indicates that the lasing wavelength \( \lambda_i \) is shorter than the conversion efficiency peak and decrease the lasing wavelength \( \lambda_i \) when the comparison indicates that the lasing wavelength \( \lambda_i \) is longer than the conversion efficiency peak.

[0026] For example, where the controller 130 is programmed to control the lasing wavelength \( \lambda_\chi \) of the semiconductor laser 110 by controlling the temperature \( T\chi \) of the wavelength selective section of the laser 110, the lasing wavelength \( \lambda_i \) will increase with increasing heater current. If this heater current is subject to modulation by the modulated feedback control signal, increases in the modulated feedback control signal will correspond to increases in the temperature \( T\chi \) of the wavelength selective section and increases in the lasing wavelength \( \lambda_i \). Accordingly, the position of the lasing wavelength \( \lambda_\chi \), relative to the conversion efficiency peak illustrated in Fig. 3, can be determined by comparing the behavior of the modulated feedback control signal with the modulated output intensity \( I(2V_{MOD}) \) of the wavelength conversion device. If an increase in the modulated feedback control signal, as is represented by \( \lambda_{MOD} \) in Fig. 3, serves to increase the magnitude of the modulated output intensity \( I(2V_{MOD}) \) by \( \Delta I \), one can deduce that the lasing wavelength \( \lambda_i \) must reside on the
short wavelength side of the conversion efficiency peak because the increasing feedback control signal would be in phase with the increasing portion of the conversion efficiency curve. Alternatively, if an increase in the modulated feedback control signal serves to decrease the magnitude of the modulated output intensity \( I(2V_{MOD}) \) by \( \Delta I \), one can deduce that the lasing wavelength \( \lambda_i \) must reside on the long wavelength side of the conversion efficiency peak because, to reduce the output intensity, the increasing feedback control signal must define wavelength values that are out of phase with the conversion efficiency curve. Suitable corrections to the lasing wavelength control signal can be made once the position of the lasing wavelength \( \lambda_i \) relative to the conversion efficiency peak has been determined.

[0027] Analogous approaches can be made in cases where mechanisms other than heater current dominate control of the lasing wavelength. For example, in the case of a DBR laser, when the DBR injection current is low, the carrier effect attributable to modulated DBR injection current is typically stronger than the thermal effect attributable to the injection current and the lasing wavelength actually decreases with increases in the modulated feedback control signal. Accordingly, the inverse of the above-described modulation/wavelength relationship would control. More specifically, if an increase in the modulated feedback control signal serves to decrease the magnitude of the modulated output intensity, one can deduce that the lasing wavelength must reside on the short wavelength side of the conversion efficiency peak because the increasing feedback control signal must be out of phase with the increasing portion of the conversion efficiency curve.

[0028] The present inventors have recognized benefits attributable to incorporating a feed forward control scheme with the aforementioned feedback control scheme. Specifically, the present invention contemplates the use of a feed forward scheme designed to place the lasing wavelength in the approximate vicinity of the conversion efficiency peak prior to application of the feedback control procedures described herein. According to this aspect of the present invention, the controller is programmed to execute feed forward control of a parameter of the semiconductor laser as a function of the gain current \( I_G \). Typically, the gain current \( I_G \) will vary continuously over time because it carries variable intensity data. This intentional variation of \( I_G \) produces unintentional temperature variation of the wavelength selective section, resulting in unintentional wavelength variation. This variation of wavelength can be at least partially corrected for in a feed forward manner by controlling the temperature \( T_\lambda \) of the wavelength selective section, the amount of current \( I_\lambda \) injected into the wavelength
selective section, or both, as a function of the gain current $I_Q$. For example, the feed forward control can be manifested in the encoded data signal by referring to a lookup table that correlates selected gain currents $I_G$ with corresponding temperature $T_A$ or DBR control signal values. For example, referring to Fig. 4, generally, as output intensity $I$ increases with increasing gain current $I_Q$, the optimum DBR voltage $V_{DBR}$ applied to a DBR heater of a DBR laser will fall towards a minimum value. Accordingly, the aforementioned lookup table, or some other means, can be used to establish a set of DBR voltages ($\text{FF} V_{DBR}$) that are associated with corresponding gain currents $I_Q$. In this manner, feed forward action can be used in the present invention to place the lasing wavelength control signal in the vicinity of the peak of the conversion efficiency curve prior to application of one of the feedback techniques described herein. This aspect of the present invention is particularly useful where the conversion efficiency curve is complex and includes one or more minor peaks near the maximum efficiency peak.

[0029] The inventors realize that in order for the modulated feedback signal to effectively modulate the lasing wavelength of a DBR laser, a technique called Return-to-Zero (RZ) is useful. Since a DBR laser sometimes has the tendency to lock to a particular cavity mode, the modulation of the lasing wavelength can be very small even if the modulated feedback signal is applied to the wavelength selective section, reducing the effectiveness of the control scheme. To make the lasing wavelength more responsive to the modulated feedback signal, the gain-section drive current is periodically reset to zero.

[0030] Fig. 6 illustrates the manner in which a programmable controller 130 according to one embodiment of the present invention can be configured to incorporate the functionality of the aforementioned feed forward 150 and feedback 160 control segments. The feed forward control segment 150 can include a lookup table 150A, as is noted above, and a suitable signal filtering component 150B. The feedback control segment 160 is configured to generate the aforementioned periodic frequency $V_{MOD}$ of the modulated feedback control signal and further includes signal filtering components 160A, gain current $I_G$ scaling logic 160B, and logic 160C for comparing the modulated feedback control signal with the scaled feedback control signal. More specifically, according to particular embodiments of the present invention, the controller 130 can be programmed to compare a feedback signal 155 representing the intensity of the frequency-converted modulated output intensity $I(2V_{MOD})$ with the modulated feedback control signal 165 by integrating the product of the modulated feedback control
signal and the modulated output intensity $I(2V_{\text{MOD}})$ over a given modulation period. The controller can also be programmed to compensate for delay introduced in filtering and detecting the modulated output intensity $I(2V_{\text{MOD}})$ by shifting the modulated feedback control signal in time relative to the modulated output intensity $I(V_{\text{MOD}})$ prior to integration. Output signals representing the aforementioned comparison, the modulated feedback control signal, and the output of the feed forward segment 150 are combined via a suitable summation component 170 and are used to drive the DBR section of the laser 110.

[0031] Fig. 6 also illustrates a signal normalization mechanism that can be incorporated in the methodology of the present invention to enhance analysis of conversion efficiency, as opposed to merely frequency-converted output intensity. Specifically, referring to Fig. 6, the controller 130 can be programmed to divide the filtered feedback signal by the filtered gain current signal to normalize the resulting control signal. As a result, the feedback control segment 160 will have similar responses to relatively low and relatively high laser power and will be less susceptible to variations in the frequency content of the input data signal. It is noted that the frequencies values listed for the various signal filtering components are presented as illustrative examples only and should not be taken to limit the scope of the present invention.

[0032] Processes according to specific embodiments of the present invention can be described with reference to the flow chart of Fig. 7, where the gain current data signal is illustrated as an input for controlling lasing intensity and lasing wavelength (see data signal input 202 and intensity and wavelength control step 204) and the modulated feedback control signal is illustrated as an input for modulating the laser (see feedback signal input 206 and wavelength modulation step 208). The position of the lasing wavelength $\lambda_i$, relative to the conversion efficiency peak is determined in step 210 from data representing the modulated output intensity $I(2V_{\text{MOD}})$ (see input 212) and the modulated feedback control signal (see input 214). Suitable corrections to the lasing wavelength control signal are made once the position of the lasing wavelength $\lambda_i$ relative to the conversion efficiency peak has been determined (see wavelength control signal adjustment step 216). The feedback loop can be run in continuous mode.

[0033] According to one aspect of the present invention, care is taken to ensure that the periodic frequency $V_{\text{MOD}}$ of the modulated feedback control signal has very little content at
the frequency of the data signal to avoid confusion between the data signal and the feedback control signal. For example, in the case of a video projection system, the periodic frequency $V_{\text{MOD}}$ of the modulated feedback control is set to a value where the content of the video signal, and its higher order harmonics, are at a minimum. For video projection systems that operate at frame rates of about 60 Hz, the periodic frequency $V_{\text{MOD}}$ of the modulated feedback control signal, as manifested in a modulated output intensity $I(V_{\text{MOD}})$ of the wavelength conversion device, can be set to be about 0.5, 1.5, 2.5, 3.5, etc., times the value of the periodic frequency $V_{\text{DATA}}$ of the gain current $I_G$. In this manner, those practicing this aspect of the present invention can ensure that portions of the signal representing the video data can be discriminated from portions of the signal representing the modulated feedback control signal. Typically, it is most convenient to establish the periodic frequency $V_{\text{MOD}}$ of the modulated feedback control signal at a higher value than the periodic frequency $V_{\text{DATA}}$ of the gain current $I_G$.

[0034] It is also significant to note that the use of the modulated feedback control signal described herein can also smooth or average-out sudden wavelength changes in the laser output, particularly where the laser is shut down very frequently during normal data signal processing. Accordingly, aspects of the present invention are particularly well-suited for laser control schemes where the laser is shut down very frequently during normal data signal processing, including, for example, the control schemes taught in commonly assigned, copending U.S. Patent Application Serial No. 11/549,856, filed October 16, 2006, for WAVELENGTH CONTROL IN SEMICONDUCTOR LASERS (D 20106 / SP06-157), the disclosure of which is incorporated herein by reference.

[0035] Additional embodiments of the present invention contemplate control of the periodic lasing intensity of the semiconductor laser such that the periodic frequency $V_{\text{MOD}}$ of the modulated feedback control signal exceeds the corresponding frame rate of the encoded data signal. Accordingly, for applications of the present invention where the periodic frequency $V_{\text{DATA}}$ of the gain current $I_G$ represents video content projected across a pixel array, it can be advantageous to ensure that the periodic frequency $V_{\text{MOD}}$ of the modulated feedback control signal is high enough to ensure that the projection system cycles through a plurality of modulated feedback control signal periods for each image pixel. In addition, it can be helpful
to ensure that the lasing wavelength $\lambda_i$ of the semiconductor laser is controlled to ensure that
that the amplitude of the modulated output intensity $I(V_{\text{MOD}})$ is a mere fraction of the
amplitude of the data signal output intensity $I(V_{\text{DATA}})$.

[0036] Alternatively, or additionally, under some circumstances it may be beneficial to
ensure that the lasing wavelength $\lambda_i$ of the semiconductor laser is modulated with a
modulated feedback control signal that comprises multiple frequency components. Laser
projection can thus be enhanced by comparing the modulated output intensity $I(V_{\text{MOD}})$ with
more than a single frequency component of the modulated feedback control signal because a
particular modulation frequency may perform better than others under particular
circumstances. If simultaneous modulation at a plurality of frequencies is not practical or
desired, it is contemplated that the controller can be programmed to modulate the lasing
wavelength $\lambda_i$ using a periodic frequency $V_{\text{MOD}}$ that changes over time in a random or
periodic fashion. Further, it is contemplated that the waveform shape and/or amplitude of the
feedback signal can also be changed over time to enhance the feedback operation. Finally, it
is noted that the modulated feedback control signal can be modulated to carry encoded
correlation data for subsequent adjustment of the wavelength control signal.

[0037] For DBR lasers, and many other semiconductor lasers that utilize a gain section and
a wavelength selective section, proper control of the DBR section of the laser is dictated by
the gain section to DBR crosstalk. Basically, as the gain section is driven with a variety of
gain current signals, part of the heat generated in the gain section gets transferred to the DBR
section. Accordingly, care can be taken to compensate for this crosstalk by applying a
crosstalk compensation signal to the DBR section. In general, the crosstalk effect is a
relatively slow process, e.g., on the order of 10-30 ms, because the heat takes some time to
propagate from the gain section to the DBR section. Accordingly, from this perspective the
DBR control loop need not be excessively fast and the frequency of the feedback modulation
signal can be about 100 Hz. However, depending on the parameters of the laser in use, a
second mechanism may generate much faster crosstalk, particularly where photons generated
in the gain section get absorbed in the DBR section and generate some heating in the DBR
section. The resulting heat is transferred quasi-instantly, or at least much faster than the
relatively slow crosstalk. Indeed, it is contemplated that this quasi-instant crosstalk
mechanism can generate 25% power fluctuations over a time scale on the order of about 1 $\mu$s.
To compensate for these fluctuations, those practicing the present invention can use modulation frequencies in the feedback signal well above 100Hz. According to another contemplated approach the relatively fast DBR-to-gain crosstalk can be calibrated and controlled in an open loop and applied in addition to the aforementioned, relatively slow feedback loop.

It is noted that although the present invention has been described with reference to control of the wavelength selective or DBR section of a semiconductor laser, similar benefits may be enjoyed by controlling those properties of the phase section of a DBR laser that affect lasing wavelength.

Returning to Fig. 5, it is noted that the programmable controller 130 may further comprise a frequency-based filter configured to discriminate between the periodic frequency $V_{MOD}$ of the modulated feedback control signal and the periodic frequency $V_{DATA}$ of the gain current $I_G$. By utilizing a suitably configured optical splitter 140, the vast majority $I_{(DISPLAY)}$ of the signal output from the wavelength conversion device 120 can projected without filtering and a small portion $I_{(FEEDBACK)}$ of the output signal can be directed to the programmable controller 130 and associated circuitry. The controller 130 is programmed to remove the content of the encoded data signal from a portion of the data signal output intensity to permit comparison of the modulated output intensity $I(V_{MOD})$ with the modulated feedback control signal.

Other embodiments of the present invention contemplate controllers that are programmed to determine whether the lasing wavelength $\lambda$ is shorter or longer than the conversion efficiency peak of the wavelength conversion device 120 by comparing noise fluctuation in the modulated output intensity $I(V_{MOD})$ with the modulated feedback control signal. For example, the controller can be programmed to correlate increases or decreases in the amplitude of the modulated feedback control signal with corresponding increases or decreases in the amount of noise in the modulated output intensity $I(V_{MOD})$ to determine whether modulated feedback control signal is in phase with or out of phase with the conversion efficiency curve of the wavelength conversion device. Still other embodiments of the present invention contemplate controllers that are programmed to determine whether the lasing wavelength $\lambda$ is shorter or longer than the conversion efficiency peak by comparing amplitude fluctuation in the modulated output intensity $I(V_{MOD})$ with the modulated feedback.
control signal. For example, controllers according to this aspect of the present invention can be programmed to correlate increases or decreases in the amplitude of the modulated feedback control signal with corresponding increases or decreases in the amplitude of the modulated output intensity $I(V_{MOD})$ to determine whether modulated feedback control signal is in phase with the conversion efficiency curve of the wavelength conversion device.

[0041] It is noted that reference herein to single mode lasers or lasers configured for single mode optical emission should not be taken to restrict the scope of the present invention to lasers that operate in a single mode exclusively. Rather, the references herein to single mode lasers or lasers configured for single mode optical emission should merely be taken to imply that lasers contemplated according to particular embodiments of the present invention will be characterized by an output spectrum where a single mode of broad or narrow bandwidth is discernable therein or by an output spectrum that is amenable to discrimination of a single mode there from through suitable filtering or other means.

[0042] A multi-tone image can be generated by image projection systems according to the present invention by configuring the image projection electronics and the corresponding laser drive currents to establish a pixel intensity that varies across an array of image pixels. For example, referring to Fig. 2, a projection system may comprise an image source (S) generating a single or multi-color image data stream, image projection software and associated electronics (S/E) for generating a laser drive signal for each primary image color, a laser driver (D) generating respective laser drive currents for individual lasers (LD) configured to generate each primary image color, and scanning and projection optics (O) that operate to generate a single or multi-color projected image (I) comprising an array of image pixels. Where the programmable light source is comprised within a pixel-based laser projection system, controllers according to the present invention may be programmed to control the periodic lasing intensity of the semiconductor laser such that the encoded data signal comprises a plurality of encoded data periods corresponding to the frame rate of the projection system.

[0043] It is contemplated that programmable light sources according to the present invention may comprise a plurality of semiconductor lasers, at least one of which is coupled to the wavelength conversion device and controlled according to one or more of the control procedures contemplated by the present invention. Further detail concerning the configuration of scanning laser image projection systems and the manner in which varying
pixel intensities are generated across an image may be gleaned from a variety of readily available teachings on the subject. Although the present invention is clearly applicable to pixel-based projection systems, it is contemplated that other projection systems, such as spatial light modulator based systems (including digital light processing (DLP), transmissive LCD, and liquid crystal on silicon (LCOS)), incorporating laser-based light sources may also benefit from the wavelength control techniques described herein.

[0044] Reference is made throughout the present application to various types of currents. For the purposes of describing and defining the present invention, it is noted that such currents refer to electrical currents. Further, for the purposes of defining and describing the present invention, it is noted that reference herein to "control" of an electrical current does not necessarily imply that the current is actively controlled or controlled as a function of any reference value. Rather, it is contemplated that an electrical current could be controlled by merely establishing the magnitude of the current.

[0045] It is to be understood that the preceding detailed description of the invention is intended to provide an overview or framework for understanding the nature and character of the invention as it is claimed. It will be apparent to those skilled in the art that various modifications and variations can be made to the present invention without departing from the spirit and scope of the invention. Thus, it is intended that the present invention cover the modifications and variations of this invention provided they come within the scope of the appended claims and their equivalents.

[0046] For the purposes of defining and describing the present invention, it is noted that reference herein to values that are "on the order of" a specified magnitude should be taken to encompass any value that does not vary from the specified magnitude by one or more orders of magnitude. It is also noted that one or more of the following claims recites a controller "programmed to" execute one or more recited acts. For the purposes of defining the present invention, it is noted that this phrase is introduced in the claims as an open-ended transitional phrase and should be interpreted in like manner as the more commonly used open-ended preamble term "comprising." In addition, it is noted that recitations herein of a component of the present invention, such as a controller being "programmed" to embody a particular property, function in a particular manner, etc., are structural recitations, as opposed to recitations of intended use. More specifically, the references herein to the manner in which a component is "programmed" denotes an existing physical condition of the component and, as such, is to be taken as a definite recitation of the structural characteristics of the component.
It is noted that terms like "preferably," "commonly," and "typically," when utilized herein, are not intended to limit the scope of the claimed invention or to imply that certain features are critical, essential, or even important to the structure or function of the claimed invention. Rather, these terms are merely intended to highlight alternative or additional features that may or may not be utilized in a particular embodiment of the present invention. Further, it is noted that reference to a value, parameter, or variable being a "function of another value, parameter, or variable should not be taken to mean that the value, parameter, or variable is a function of one and only one value, parameter, or variable.

For the purposes of describing and defining the present invention it is noted that the term "substantially" is utilized herein to represent the inherent degree of uncertainty that may be attributed to any quantitative comparison, value, measurement, or other representation. The term "substantially" is also utilized herein to represent the degree by which a quantitative representation, e.g., "substantially above zero," varies from a stated reference, e.g., "zero," and should be interpreted to require that the quantitative representation varies from the stated reference by a readily discernable amount.
CLAIMS

What is claimed is:

1. A programmable light source comprising at least one semiconductor laser (10, 110), a wavelength conversion device (20, 120), and a laser controller (130) programmed to operate the semiconductor laser (10, 110) wherein the semiconductor laser (10, 110) comprises a wavelength selective section and a gain section, an output of the semiconductor laser (10, 110) is coupled to an input of the wavelength conversion device (20, 120), and the laser controller (130) is programmed to:

   control periodic lasing intensity of the semiconductor laser (10, 110) by controlling an amount of gain current \( I_G \) injected into the gain section of the semiconductor laser (10, 110), wherein a periodic frequency \( V_{DATA} \) of the gain current \( I_G \) represents an encoded data signal;

   control the lasing wavelength \( \lambda_i \) of the semiconductor laser (10, 110) by using a wavelength control signal to control the temperature \( T \) of the wavelength selective section, an amount of current \( I_\chi \) injected into the wavelength selective section, or both;

   modulate the lasing wavelength \( \lambda_i \) of the semiconductor laser (10, 110) by using a modulated feedback control signal to control the temperature \( T \) of the wavelength selective section, the amount of current \( I_\chi \) injected into the wavelength selective section, or both, wherein the periodic frequency \( V_{MOD} \) of the modulated feedback control signal, as manifested in a modulated output intensity of the wavelength conversion device (20, 120), is substantially different than the periodic frequency \( V_{DATA} \) of the gain current \( I_G \), as manifested in a data signal output intensity of the wavelength conversion device (20, 120);

   determine whether the lasing wavelength \( \lambda_i \) is shorter or longer than a conversion efficiency peak of the wavelength conversion device (20, 120) by comparing the modulated output intensity with the modulated feedback control signal;

   adjust the wavelength control signal to increase the lasing wavelength \( \lambda_i \) when the comparison indicates that the lasing wavelength \( \lambda_i \) is shorter than the conversion efficiency peak and decrease the lasing wavelength \( \lambda_i \) when the comparison indicates that the lasing wavelength \( \lambda_i \) is longer than the conversion efficiency peak; and

   control the lasing wavelength \( \lambda_i \) of the semiconductor laser (10, 110) by using the adjusted wavelength control signal.
2. A programmable light source as claimed in claim 1 wherein the periodic frequency $V_{\text{MOD}}$ of the modulated feedback control signal, as manifested in a modulated output intensity of the wavelength conversion device (20, 120), is additionally different than higher frequency harmonics of the periodic frequency $V_{\text{DATA}}$ of the gain current $I_G$, as manifested in a data signal output intensity of the wavelength conversion device (20, 120).

3. A programmable light source as claimed in claim 1 wherein the controller is programmed to:

   - control the periodic lasing intensity of the semiconductor laser (10, 110) such that the encoded data signal comprises a plurality of encoded data periods; and
   - control the periodic frequency $V_{\text{MOD}}$ of the modulated feedback control signal such that each of the encoded data periods comprises a plurality of modulated feedback control signal periods.

4. A programmable light source as claimed in claim 1 wherein the controller is programmed to modulate the lasing wavelength $\lambda$ of the semiconductor laser (10, 110) such that the amplitude of the modulated output intensity is a fraction of the amplitude of the data signal output intensity.

5. A programmable light source as claimed in claim 1 wherein the controller is programmed to:

   - modulate the lasing wavelength $\lambda_i$ of the semiconductor laser (10, 110) using a modulated feedback control signal comprising multiple frequency components; and
   - compare the modulated output intensity with a plurality of the frequency components of the modulated feedback control signal.

6. A programmable light source as claimed in claim 1 wherein the controller is programmed to modulate the lasing wavelength $\lambda_i$ of the semiconductor laser (10, 110) using a modulated feedback control signal comprising a periodic frequency $V_{\text{MOD}}$ that changes over time in a random or periodic fashion.
7. A programmable light source as claimed in claim 1 wherein the modulated feedback control signal is modulated to carry encoded correlation data for subsequent adjustment of the wavelength control signal.

8. A programmable light source as claimed in claim 1 wherein the programmable light source further comprises a frequency-based filter configured to discriminate between the periodic frequency $\nu_{\text{MOD}}$ of the modulated feedback control signal and the periodic frequency $\nu_{\text{DATA}}$ of the gain current $I_G$, as manifested in the data signal output intensity of the wavelength conversion device (20, 120).

9. A programmable light source as claimed in claim 1 wherein the controller is further programmed to remove the content of the encoded data signal from a portion of the data signal output intensity to permit comparison of the modulated output intensity with the modulated feedback control signal.

10. A programmable light source as claimed in claim 1 wherein the controller is programmed to determine whether the lasing wavelength $\lambda_i$ is shorter or longer than a conversion efficiency peak of the wavelength conversion device (20, 120) by comparing noise fluctuation in the modulated output intensity with the modulated feedback control signal.

11. A programmable light source as claimed in claim 1 wherein the controller is programmed to determine whether the lasing wavelength $\lambda_i$ is shorter or longer than a conversion efficiency peak of the wavelength conversion device (20, 120) by comparing amplitude fluctuation in the modulated output intensity with the modulated feedback control signal.

12. A programmable light source as claimed in claim 1 wherein the controller is programmed to modulate the lasing wavelength $\lambda_i$ of the semiconductor laser (10, 110) by controlling the temperature $T_{\lambda}$ of the wavelength selective section vis-a-vis (i) a thermal effect from a heater current in the wavelength selective section of the semiconductor laser (10, 110) or (ii) a thermal effect from an injection current in the gain section of the semiconductor laser (10, 110).
13. A programmable light source as claimed in claim 1 wherein the controller is programmed to modulate the lasing wavelength $\lambda_1$ of the semiconductor laser (10, 110) by controlling the amount of current $I_k$ injected into the wavelength selective section vis-a-vis a carrier effect from an injection current in the wavelength selective section of the semiconductor laser (10, 110).

14. A programmable light source as claimed in claim 1 wherein the controller is programmed to compare the modulated output intensity with the modulated feedback control signal by integrating the product of the modulated feedback control signal and the modulated output intensity over a modulation period.

15. A programmable light source as claimed in claim 14 wherein the controller is programmed to compensate for delay in detection of the modulated output intensity by shifting the modulated feedback control signal in time relative to the modulated output intensity prior to the comparison.

16. A programmable light source as claimed in claim 1 wherein the controller is programmed to execute feed forward control of the temperature $T_X$ of the wavelength selective section, the amount of current $I_X$ injected into the wavelength selective section, or both, as a function of the gain current $I_Q$.

17. A programmable light source as claimed in claim 16 wherein the feed forward control is manifested in the encoded data signal.

18. A programmable light source as claimed in claim 1 wherein:

the programmable light source comprises a plurality of semiconductor lasers (10, 110); and

at least one of the semiconductor lasers is coupled to the wavelength conversion device (20, 120) and is subject to control according to the conditions recited in claim 1 such that the data signal output intensity of the wavelength conversion device (20, 120) and the lasing wavelength of the remaining semiconductor lasers occupy distinct portions of the optical spectrum.
19. A programmable light source comprising at least one semiconductor laser (10, 110), a wavelength conversion device (20, 120), and a laser controller (130) programmed to operate the semiconductor laser (10, 110) wherein the semiconductor laser (10, 110) comprises a wavelength selective section, a phase matching section, and a gain section, an output of the semiconductor laser (10, 110) is coupled to an input of the wavelength conversion device (20, 120), and the laser controller (130) is programmed to:

control periodic lasing intensity of the semiconductor laser (10, 110) by controlling an amount of gain current $I_G$ injected into the gain section of the semiconductor laser (10, 110), wherein a periodic frequency $V_{\text{DATA}}$ of the gain current $I_G$ represents an encoded data signal;

control the lasing wavelength $\lambda_1$ of the semiconductor laser (10, 110) by using a wavelength control signal to control the temperature $T_\lambda$ of the wavelength selective or phase matching section, an amount of current $I_\lambda$ injected into the wavelength selective section or phase matching section, or combinations thereof;

modulate the lasing wavelength $\lambda_1$ by using a modulated feedback control signal to control the temperature $T_\lambda$ of the wavelength selective or phase matching sections, the amount of current $I_\lambda$ injected into the wavelength selective or phase matching sections, or combinations thereof, wherein the periodic frequency $V_{\text{MOD}}$ of the modulated feedback control signal, as manifested in a modulated output intensity of the wavelength conversion device (20, 120), is substantially different than the periodic frequency $V_{\text{DATA}}$ of the gain current $I_G$, as manifested in a data signal output intensity of the wavelength conversion device (20, 120);

determine whether the lasing wavelength $\lambda_i$ is shorter or longer than a conversion efficiency peak of the wavelength conversion device (20, 120) by comparing the modulated output intensity with the modulated feedback control signal;

adjust the wavelength control signal to increase the lasing wavelength $\lambda_i$ when the comparison indicates that the lasing wavelength $\lambda_i$ is shorter than the conversion efficiency peak and decrease the lasing wavelength $\lambda_i$ when the comparison indicates that the lasing wavelength $\lambda_i$ is longer than the conversion efficiency peak; and

control the lasing wavelength $\lambda_i$ of the semiconductor laser (10, 110) by using the adjusted wavelength control signal.
20. A method of operating a programmable light source comprising at least one semiconductor laser (10, 110) and a wavelength conversion device (20, 120), wherein the semiconductor laser (10, 110) comprises a wavelength selective section and a gain section and an output of the semiconductor laser (10, 110) is coupled to an input of the wavelength conversion device (20, 120), the method comprising:

controlling the periodic lasing intensity of the semiconductor laser (10, 110) by controlling an amount of gain current \( I_G \) injected into the gain section of the semiconductor laser (10, 110), wherein a periodic frequency \( V_{DATA} \) of the gain current \( I_G \) represents an encoded data signal;

controlling the lasing wavelength \( \lambda_i \) of the semiconductor laser (10, 110) by using a wavelength control signal to control the temperature \( T_\lambda \) of the wavelength selective section, an amount of current \( I_\xi \) injected into the wavelength selective section, or both;

modulating the lasing wavelength \( \lambda_i \) of the semiconductor laser (10, 110) by using a modulated feedback control signal to control the temperature \( T_\lambda \) of the wavelength selective section, the amount of current \( I_\xi \) injected into the wavelength selective section, or both, wherein the periodic frequency \( V_{MOD} \) of the modulated feedback control signal, as manifested in a modulated output intensity of the wavelength conversion device (20, 120), is substantially different than the periodic frequency \( V_{DATA} \) of the gain current \( I_G \), as manifested in a data signal output intensity of the wavelength conversion device (20, 120);

determining whether the lasing wavelength \( \lambda_i \) is shorter or longer than a conversion efficiency peak of the wavelength conversion device (20, 120) by comparing the modulated output intensity with the modulated feedback control signal;

adjusting the wavelength control signal to increase the lasing wavelength \( \lambda_i \) when the comparison indicates that the lasing wavelength \( \lambda_i \) is shorter than the conversion efficiency peak and decrease the lasing wavelength \( \lambda_i \) when the comparison indicates that the lasing wavelength \( \lambda_i \) is longer than the conversion efficiency peak; and

controlling the lasing wavelength \( \lambda_i \) of the semiconductor laser (10, 110) by using the adjusted wavelength control signal.
FIG. 5
A. CLASSIFICATION OF SUBJECT MATTER

INV. H01S5/0687
ADD. H01S5/06 H01S5/0683

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)
H01S H04N H04B

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

Electronic data base consulted during the international search (name of data base and where practical, search terms used)
EPO-Internal, WPI Data, INSPEC, COMPENDEX

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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<td>JP 2006 011332 A (CANON KK) 12 January 2006 (2006-01-12) abstract paragraphs [0015] - [0035]; figures 2-4,8,10</td>
<td>1-4,8,9, 12,16, 17,20</td>
</tr>
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Date of the actual completion of the international search

30 July 2008

Date of mailing of the international search report

11/08/2008

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Authorized officer

Laenen, Robert
### DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
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<tr>
<th>Category</th>
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<th>Relevant to claim No</th>
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<tr>
<td>Y</td>
<td>US 6 671 465 B1 (COHEN YACOV [US] ET AL) 30 December 2003 (2003-12-30) column 4, line 37 - column 5, line 32; figures 1,2</td>
<td>10,15</td>
</tr>
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Form PCT/ISA/210 (continuation of second sheet) (April 2005)
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<tr>
<td>US 2004066807 A1</td>
<td>08-04-2004</td>
<td>CN 1518788 A</td>
<td>04-08-2004</td>
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<tr>
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<td></td>
<td>WO 03001635 A1</td>
<td>03-01-2003</td>
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<td>12-01-2006</td>
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<tr>
<td>US 2006182441 A1</td>
<td>17-08-2006</td>
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