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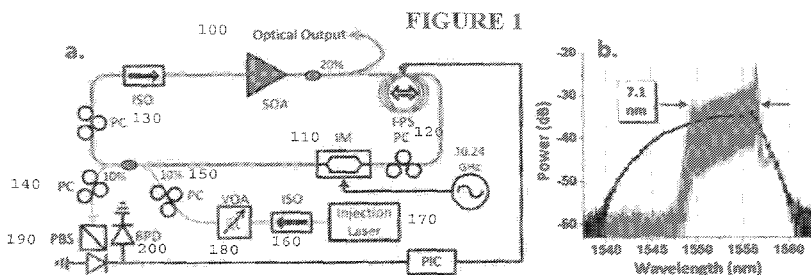
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(54) Title: STABILIZATION OF AN INJECTION LOCKED HARMONICALLY MODE-LOCKED LASER VIA POLARIZA-
TION SPECTROSCOPY FOR FREQUENCY COMB GENERATION

(57) Abstract: Stabilization of an injection locked optical frequency comb is achieved through polarization spectroscopy of an active laser cavity, eliminating optical PM sidebands inherent in previous stabilization methods. Optical SNR of 35 dB is achieved. A monolithic AlInGaAs quantum well Fabry-Prot laser injection locked to a passively mode-locked monolithic laser is presented here. The FP laser cavity can be used as a true linear interferometric intensity modulator for pulsed light.

TITLE OF THE INVENTION**STABILIZATION OF AN INJECTION LOCKED
HARMONICALLY MODE-LOCKED LASER VIA
POLARIZATION SPECTROSCOPY FOR FREQUENCY
COMB GENERATION****Priority Data and Incorporation by Reference**

[0001] This application claims benefit of priority to U.S. Provisional Patent Application No. 61/622,599 filed April 11, 2012 which is incorporated by reference in its entirety.

BACKGROUND OF THE INVENTION**Field of the Invention**

[0002] The invention of this application focuses on advances in photonic frequency combs. These find a wide variety of applications, including data harvesting and pattern recognition. An example of a system taking advantage of optical signal processing using stabilized optical frequency combs can be found in U.S. Patent No. 7,917,039, incorporated-herein-by reference. Related improvements in optical networks are also set forth in U.S. Patent No. 7,848,655. This invention focuses on improved signal processing systems, employing an improved frequency modulator.

Background of the Invention

[0003] The proliferation of applications for photonic frequency combs has fueled the search for sources which can deliver large optical frequency component spacing, narrow optical linewidth, and excellent RF phase noise and stability with small footprints, electrical efficiency, and ease of use. For example, applications such as optical arbitrary waveform generation and coherent communication require access to individual comb components necessitating comb spacing in the multi-gigahertz region [1]. The burgeoning field of multi-heterodyne spectroscopy utilizes a narrow linewidth frequency comb to probe the phase and

amplitude information of an unknown signal with different periodicity [2]. This field can also benefit from easily tunable frequency comb spacing by granting control over the detuning frequency between the two signal pulse-trains.

[0004] Continuous wave (CW) optical injection locking of semiconductor-based harmonically mode-locked lasers has been shown to produce tunable, gigahertz-spaced frequency comb outputs with high optical and RF signal to noise ratio (SNR), and reduced phase and amplitude noise [3]. By suppressing all but one optical axial mode group via gain competition, an optical frequency comb is generated at the repetition frequency, which is then easily tunable at steps equal to the fundamental cavity frequency, typically tens of MHz. Stand-alone sources are also possible using injection locking in a Coupled Opto-Electronic Oscillator (COEO).

[0005] Such injection locking schemes necessitate active stabilization of the laser fiber cavity relative to the injection frequency. Previously, a modified Pound-Drever-Hall (PDH) scheme has been used which requires phase modulation (PM) of the injection signal before injection [3]. An inherent effect of this is that the PM sidebands are injected into the cavity and are then modulated at the repetition rate, producing unwanted carrier sidebands in RF and optical spectra.

[0006] As those of skill in the art will recognize, improvements in optical signal processing systems also benefit from improvements of the elements of those systems. Intensity modulators are one of the key components in signal processing, optical communication and photonic analog to digital converters (ADC). Recently, a linear intensity modulator based on an injection locked resonant cavity with gain has been shown and experimental results for a CW input light have been demonstrated. It is well known that an injection locked resonant cavity with gain serves as an arcsine phase modulator [6]. When the arcsine phase modulated light, which is a function of frequency detuning between the cavity

and the injection seed, combines with reference arm, it produces an intensity modulated CW light directly proportional to modulating signal [7].

[0007] The linearity of the response of this modulator and the possibility of gain at the output are inherent in the above design and no linearization technique is used. This technique has shown 95 dB signal to noise ratio and 120 dB Hz^{2/3} spur-free dynamic range using a VCSEL as the resonant cavity, however, it is limited to using CW light. To adapt this technique for input light signals that are pulsed and periodic, one must use a resonant cavity with multiple resonances within the gain bandwidth.

SUMMARY OF THE INVENTION

[0008] In this application, long-term cavity stabilization is performed with a polarization spectroscopy scheme first put forth by Hänsch and Couillaud [4], significantly reducing the complexity of the system while eliminating unwanted optical and RF sidebands inherent in the previous modified PDH stabilization. While the Hänsch-Couillaud (HC) method has been previously shown in single mode laser systems [5], this is the first time an injection locked, harmonically mode-locked system for the generation and stabilization of a high quality optical frequency comb, important for multi-heterodyne detection, has been advanced.

[0009] To provide for enhanced intensity modulation, a shift in design is required. Use of a resonant cavity with multiple resonances within the gain bandwidth suggests the use of a Fabry-Pérot laser (FPL) chip as the resonant cavity, where the free spectral range of the FPL chip matches the pulse repetition frequency of the input light to be modulated. This can be realized by injection locking a FPL with the output frequency comb of a mode locked laser (MLL). In this application we disclose injection locking of a monolithic FPL to a monolithic passively MLL by matching both optical spectra and free spectral range of the lasers to realize an arcsine phase modulator. As shown in Figure 3, below, the FPL can be used in an interferometric setup, where an RF signal is used to modulate the FPL to impart arcsine phase

modulation on each injected comb. The resulting interference with the unmodulated signal from the other arm then gives us the ability to generate a true linear intensity modulator for the pulsed light.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] The accompanying drawings, which are incorporated herein and constitute part of this specification, illustrate exemplary embodiments of the invention, and, together with the general description given above and the detailed description given below, serve to explain the features of the invention.

[0011] FIG. 1(a) is a schematic of injection locked harmonically mode-locked laser with long-term stabilization via polarization spectroscopy. FIG. 1(b) is a optical spectra of harmonically mode-locked laser not subject to optical injection (black) and injection locked and stabilized via polarization spectroscopy (blue).

[0012] FIG. 2(a) is a high resolution optical spectra of harmonically mode-locked laser output showing frequency comb generation under optical injection with high OSNR. The latter curve was artificially offset by -10 dB to illustrate the absence of PM sidebands on each combline. FIG. 2(b) is a photodetected RF spectra of the injection locked laser stabilized via the two methods. Note the absence of an RF sideband 550 MHz offset from the 10.24 GHz carrier for the HC stabilization method.

[0013] FIG. 3 is a schematic diagram of linear interferometric intensity modulator for pulsed light (center) and the fabricated devices are shown (left). The schematic to the right shows the FP resonances (in black), the corresponding phase response (in red) and the injected comb lines from the MLL (in blue).

[0014] FIG. 4(a)(b) is an optical and RF spectra of the 2-section passively mode-locked FP laser (c), (d) is optical spectra of the FPL before and after injection locking (e) RF spectra

of the FPL before and after injection locking (f) auto correlation trace of the FP injection locked laser.

DETAILED DESCRIPTION OF THE INVENTION

System Description

[0015] A schematic of the laser system is shown in FIG. 1(a). The laser consists of a commercially available semiconductor optical amplifier (SOA) 100 in an external fiber ring cavity. A Mach-Zehnder style intensity modulator (IM) 110 is driven at the desired pulse repetition rate and frequency comb spacing, 10.24 GHz with ~20 dBm of RF power. Two (2) couplers are included for a laser output and injection input, in addition to multiple polarization controllers (PC) 120, 130, 140, 150 and an optical isolator (ISO) 160 to ensure unidirectional operation. A CW narrow linewidth (~1 kHz) laser 170 at 1550 nm is used as the injection seed source while the injected power is controlled using a variable optical attenuator (VOA) 180.

[0016] The injection polarization is adjusted for optimal injection locking. The SOA and IM both act as polarization discriminating devices and the injected tone experiences a phase shift while interacting with the cavity. The detection apparatus is placed at the injection coupler reflection port, where the output signal consists of the preferred injection polarization as well as the orthogonal polarization directly reflected from the cavity. A PC is used to rotate both signals such that they interfere in both outputs of a fiberized polarization beam splitter (PBS) 190. A balanced photodetector (BPD) 200 takes the difference between the two signals to produce an error signal.

[0017] FIG. 1(b) shows the optical spectrum without injection, as well as the full optical bandwidth achieved by the injection locked system, which has been observed to be constant for times greater than twenty (20) minutes. FIG. 2(a) shows the high resolution optical spectra of the harmonically mode-locked laser system centered 50 GHz below the injection

frequency. When not injection locked (black), multiple axial mode groups are allowed to lapse, resulting in a seemingly continuous spectrum due to the resolution of the optical spectrum analyzer (<100 MHz). When injection locked, a high quality comb is generated at the repetition frequency. When the cavity is stabilized using the modified PDH scheme (red), sidebands from phase modulation (550 MHz) of the injection seed laser also appear on other combs of the optical spectrum due to modulation by the intracavity IM, visible in FIG. 2(a). Accordingly, RF spurs appear 20 dB above the noise floor at offsets from the carrier frequency in the photodetected RF spectrum, shown in FIG. 2(b). When stabilized using polarization spectroscopy (blue in FIGS. 1 and 2), the high resolution optical spectrum shows a sideband-free optical frequency comb with greater than 35 dB OSNR. Accordingly, the elimination of phase modulation in the detection scheme produces a sideband-free RF spectrum with SNR of 72 dB.

[0018] Stabilization via polarization spectroscopy of an injection locked, harmonically mode-locked laser is demonstrated for the generation of 10.24 GHz-spaced optical frequency comb. Injection locking is maintained for greater than twenty (20) minutes with an OSNR of greater than 35 dB and sideband-free photodetected RF SNR of 72 dB. Widely spaced optical frequency combs with easily tunable spacing from this injection locked laser system are ideal for use in the field of multi-heterodyne spectroscopy.

Optional Information

[0019] A new and promising AlInGaAs-Inp strained quantum well material at 1.55- μ m has been used for fabricating FPL and MLLs. This material system is going to replace the conventional InGaAsP-InP material because of a larger conduction band discontinuity ($AE_c=0.72 AE_g$) and a smaller valence band discontinuity [8]. The former enables uncooled operation over a large dc bias range and the latter enables a large range of bias voltage, which in fact makes the pulses shorter. The multiple quantum well layers consist of five (5)

compressively strained wells (6 nm) and six (6) slightly tensile strained barriers (10 nm). These wells and barriers are followed by a 60 nm graded index separate-confinement heterostructure (GRINSCH) and a 60 nm AlInGaAs waveguide layer. These active regions are protected by a 20 nm of InGaAsP as a wet etch stop layer. The upper cladding is 1.6 μm of InP followed by a 50 nm of InGaAsP and 200 nm of InGaAs both being heavily doped. The fabricated monolithic integrated FPL and 2-section MLL are shown in FIG. 3. The 2.5 μm wide vertical Mesa waveguides are fabricated by standard lithography and plasma etching techniques followed by two step wet etching terminating at 1.85 μm to form a single mode waveguide. The electrical isolation between the saturable absorber (SA) and gain section is achieved by removing the first two heavily doped contact layers. BCB polymer has been used for planarization. Because of slightly different group refractive indices of the two devices which is due to different injection currents, they have to be cleaved with appropriate lengths to match the mode spacing. The FPL has a total length of 1950 μm and the 2-section MLL was cleaved with the total length of 1912 μm with a SA of 56 μm (3% of the total length) separated by 10 μm gap from the gain section.

[0020] The threshold currents of the FP and 2-section FP laser were 53mA and 55mA respectively, with slope efficiencies of 0.12 and 0.11 W/A, respectively. Passive mode-locking was achieved by forward biasing the gain section and reverse biasing the SA. With an optimized 3% SA, stable mode-locking was observed for a wide range of bias currents (from threshold to as large as three (3) times the threshold) and reverse bias voltages of -0.5V to -3.8V. The optical spectrum is centered at 1555 nm with a mode spacing of 22.15 GHz and 10 dB bandwidth of 14.1 nm.

[0021] FIG. 4 (a) and (b) show the optical and the RF spectra of the MLL with the bias current of 147mA and reverse bias of -2.8 at 20°C. FIG. 2(c) and (d) show the optical spectra of the FPL at 23°C with the bias current of 56mA before and after injection locking

respectively. These parameters were carefully tuned to match the RF tones. FIG. 4(e) shows the RF spectra of the FPL before and after injection locking with 0.1mW injection power.

[0022] Frequency pulling of the RF beat tone of the FPL to the RF tone of the MLL is observed and the RF tone of 2MHz linewidth has been measured which matches the 2-section FPL, as expected. Furthermore the optical spectrum of the FPL after injection locking is much wider, by 11nm (10 dB width). FIG. 4(f) shows the autocorrelation trace from the FP injection locked laser. The pulses are 4.6 ps if a Gaussian pulse shape is assumed. These results clearly demonstrate that the each axial modes of the FPL is coherent and locked to the injected comb from the passively MLL. By modulating the current of the injection locked FPL, one imparts arcsine phase modulation on each injected comb component. By interfering this modulated signal with its unmodulated counterpart, the desired true linear intensity modulator for pulsed light is generated.

[0023] An injection locked AlInGaAs quantum well FPL as a resonant cavity is demonstrated. The FP monolithic device is locked to a monolithic passively MLL with the same free spectral range. This injection locked FPL can be used as the resonant cavity with gain in a linear interferometric intensity modulator for pulsed light.

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- [0027] [4] T. W. Hansch and B. Couillaud, "Laser frequency stabilization by polarization spectroscopy of a reflecting reference cavity," *Optics Communications*, vol. 35, pp. 441-444, 1980.
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- [0031] [8] J. R. Karin, R. J. Helkey, D. J. Derickson, R. Nagarajan, D. S. Allin, J. E. Bowers, and R. L. Thornton, "Ultrafast dynamics in field-enhanced saturable absorbers," *Appl. Phys. Lett.*, vol. 64, pp. 676–678, 1994.
- [0032] While the present invention has been disclosed both generically, and with reference to specific alternatives, those alternatives are not intended to be limiting unless reflected in the claims set forth below. The invention is limited only by the provisions of the claims, and their equivalents, as would be recognized by one of skill in the art to which this application is directed.

WHAT IS CLAIMED IS:

1. An optical frequency comb source producing a plurality of optical frequencies on a periodic frequency grid.

2. The optical frequency comb source of Claim 1, where the periodicity of plurality of optical frequencies is tunable.

3. The optical frequency comb source of Claim 1, wherein said optical frequency comb source is injection locked by a continuous wave laser.

4. The optical frequency comb source of Claim 1, wherein said comb source comprises a phase locked loop to keep the optical frequency comb source locked to the input injection locking laser.

5. An optical signal processing system, comprising:
An injection laser controlled by a by a variable optical attenuator, in optical connection with;

An optical isolator coupled to a semiconductor optical amplifier and a light intensity modulator, and couplers for laser output and injection input.

6. The system of Claim 5, wherein said system comprises a plurality of polarization controllers.

7. The system of Claim 5, wherein said optical amplifier is a semiconductor optical amplifier.

8. The system of Claim 5, wherein said system further comprises a polarization beam splitter and a balanced photodetector.

9. An optical interferometer comprising an arc-sine phase modulator in one arm of the Interferometer.

10. The optical interferometer of Claim 9 comprising a plurality of arc-sine phase modulators in one arm, wherein each said “arc-sine” phase modulator has a different free running frequency (resonant frequency).

11. A fabry perot laser comprising a plurality of arc-sine phase modulators, each with a different of free running frequencies (resonant frequencies).

12. An optical interferometer with a fabry perot laser in one arm of the interferometer, whose resonant frequencies are periodic in frequency and match that of an input mode-locked laser, such that the input mode-locked laser injection locks the fabry perot laser.

13. A Fabry-Perot Laser chip for use as a resonant cavity, wherein the improvement comprises preparing said Fabry-Perot Laser chip from InGaAsP with an upper cladding of InP overlaying a wet etch stop layer of InGaAsP.

14. The Fabry-Perot Laser chip of Claim 13, wherein said chip is locked to a monolithically passive mode locked laser of similar free spectral range.

FIGURE 2

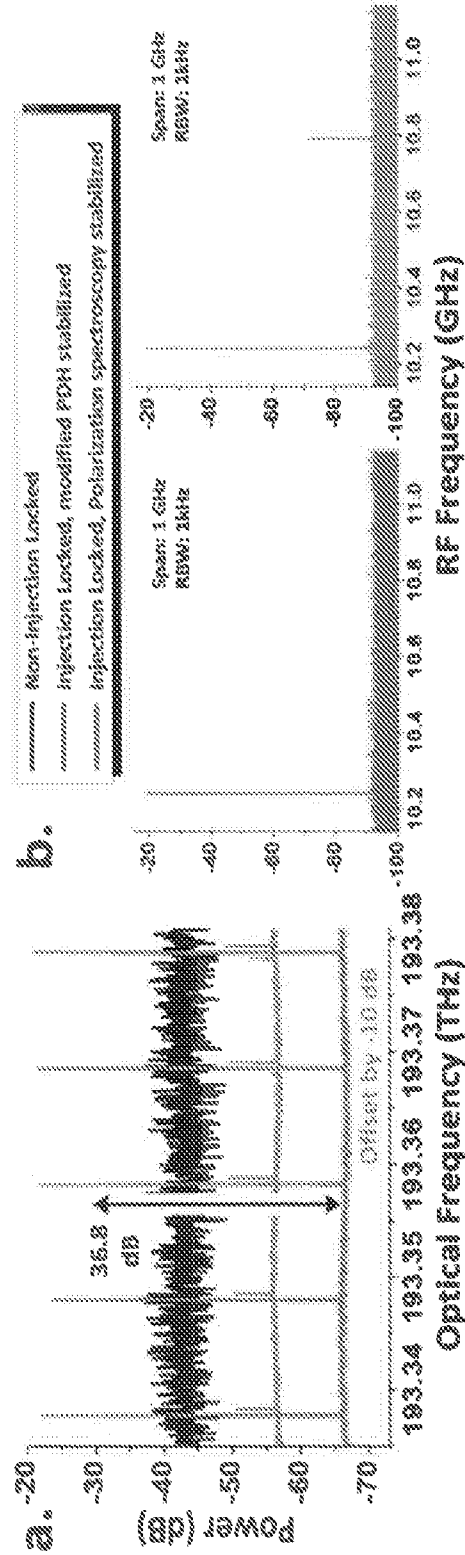


FIGURE 3

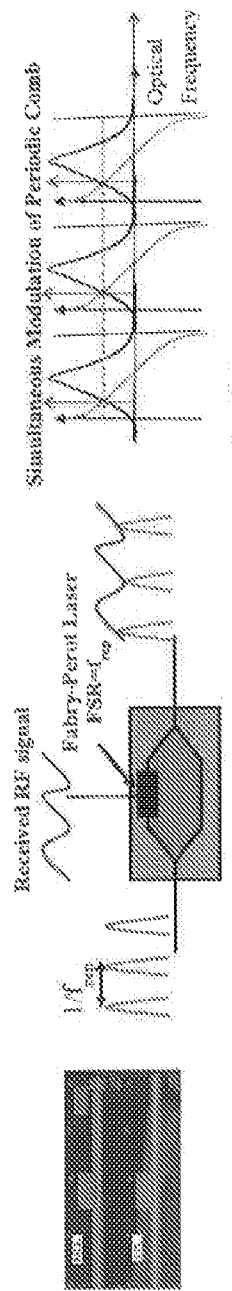
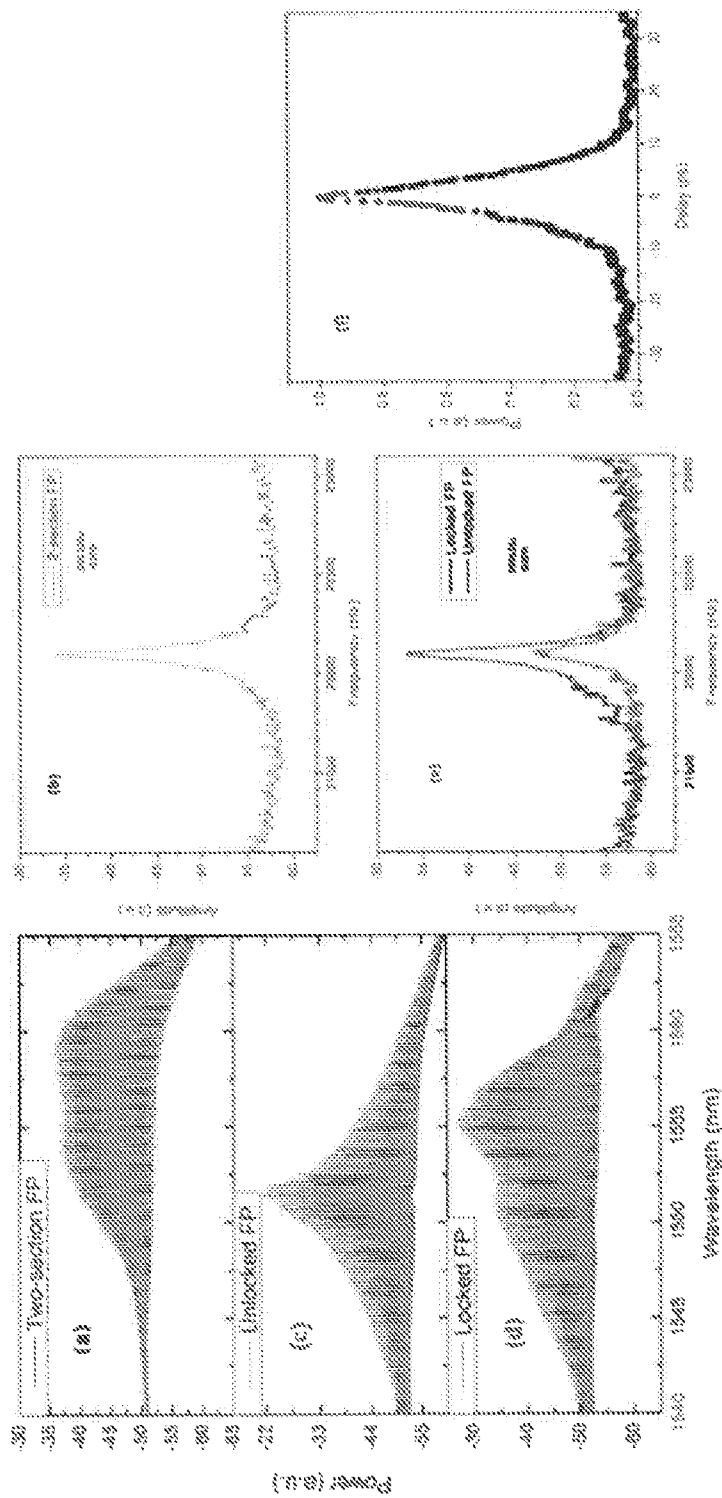


FIGURE 4



INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2013/036068

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - H01S 3/13 (2013.01)

USPC - 372/29.02

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC(8) - H01S 3/13, 3/098, 3/10 (2013.01)

USPC - 372/29.02, 18, 20, 32, 29.011

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

CPC- H01S 5/0687, 5/0683, 5/02284 (2013.01)

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

PatBase, Orbit.com, GooglePatents, ProQuest

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 7,978,740 B1 (DELFYETT et al) 12 July 2011 (12.07.2011) entire document	1
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Y		2-4
Y	US 2009/0060497 A1 (WAY) 05 March 2009 (05.03.2009) entire document	2
Y	US 4,614,913 A (HONEYCUTT et al) 30 September 1986 (30.09.1986) entire document	3-4
A	US 2008/0069159 A1 (ADEL et al) 20 March 2008 (20.03.2008) entire document	1-4
A	US 6,005,995 A (CHEN et al) 21 December 1999 (21.12.1999) abstract; column 4 lines 15-31	1-4
A	US 6,801,324 B1 (GRAY et al) 05 October 2004 (05.10.2004) entire document	1-4

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

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search

30 August 2013

Date of mailing of the international search report

18 SEP 2013

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2013/036068

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

See extra sheet.

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

1-4

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2013/036068

Continuation of Box III.

This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fees must be paid.

Group I, claims 1-4, drawn to an optical frequency comb source producing a plurality of optical frequencies on a periodic frequency grid. Group II, claims 5-8, drawn to an optical signal processing system, comprising an injection laser controlled by a by a variable optical attenuator, an optical isolator coupled to a semiconductor optical amplifier and a light intensity modulator.

Group III, claims 9-11, drawn to an optical interferometer and laser comprising an arc-sine phase modulator.

Group IV, claim 12, drawn to an optical interferometer comprising resonant frequencies that are periodic in frequency and match that of an input mode-locked laser, such that the input mode-locked laser injection locks the fabry perot laser.

Group V, claims 13-14, drawn to a Fabry-Perot Laser chip comprising a resonant cavity, wherein the improvement comprises preparing said Fabry-Perot Laser chip from InGaAsP with an upper cladding of InP overlaying a wet etch stop layer of InGaAsP.

The inventions listed as Groups I, II, III, IV and V do not relate to a single general inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons: the special technical feature of the Group I invention: an optical frequency comb source producing a plurality of optical frequencies on a periodic frequency grid, as claimed therein is not present in the invention of Groups II, III, IV or V. The special technical feature of the Group II invention: an injection laser controlled by a by a variable optical attenuator, an optical isolator coupled to a semiconductor optical amplifier and a light intensity modulator, as claimed therein is not present in the invention of Groups I, III, IV or V. The special technical feature of the Group III invention: an arc-sine phase modulator, as claimed therein is not present in the invention of Groups I, II, IV or V. The special technical feature of the Group IV invention: resonant frequencies that are periodic in frequency and match that of an input mode-locked laser, such that the input mode-locked laser injection locks the fabry perot laser, as claimed therein is not present in the invention of Groups I, II, III or V. The special technical feature of the Group V invention: a Fabry-Perot Laser chip comprising a resonant cavity, wherein the improvement comprises preparing said Fabry-Perot Laser chip from InGaAsP with an upper cladding of InP overlaying a wet etch stop layer of InGaAsP, as claimed therein is not present in the invention of Groups I, II, III or IV.

Groups I and IV lack unity of invention because even though the inventions of these groups require the technical feature of periodic optical frequencies, this technical feature is not a special technical feature as it does not make a contribution over the prior art in view of US 6,005,995 A (CHEN et al) 21 December 1999 (21.12.1999) abstract; column 4 lines 15-31.

Groups II, III, IV, V lack unity of invention because even though the inventions of these groups require the technical feature of a laser, this technical feature is not a special technical feature as it does not make a contribution over the prior art in view of US 6,801,324 B1 (GRAY et al) 05 October 2004 (05.10.2004) abstract; column 4 lines 41-52.

Groups II and III lack unity of invention because even though the inventions of these groups require the technical feature of a modulator, this technical feature is not a special technical feature as it does not make a contribution over the prior art in view of US 6,801,324 B1 (GRAY et al) 05 October 2004 (05.10.2004) abstract; column 7 lines 9-17.

Groups III and IV lack unity of invention because even though the inventions of these groups require the technical feature of an optical interferometer, this technical feature is not a special technical feature as it does not make a contribution over the prior art in view of US 6,801,324 B1 (GRAY et al) 05 October 2004 (05.10.2004) abstract; column 8 lines 23-34.

Groups III, IV, and V lack unity of invention because even though the inventions of these groups require the technical feature of a fabry perot laser with resonant frequencies, this technical feature is not a special technical feature as it does not make a contribution over the prior art in view of US 6,801,324 B1 (GRAY et al) 05 October 2004 (05.10.2004) abstract; column 1 lines 10-24; column 2 lines 21-32.

Since none of the special technical features of the Group I, II, III, IV or V inventions are found in more than one of the inventions, unity of invention is lacking.