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(54) **APPARATUS, SYSTEM, AND METHOD FOR GENERATING PHASE-LOCKED HARMONIC RF SOURCE FROM AN OPTICAL PULSE TRAIN**

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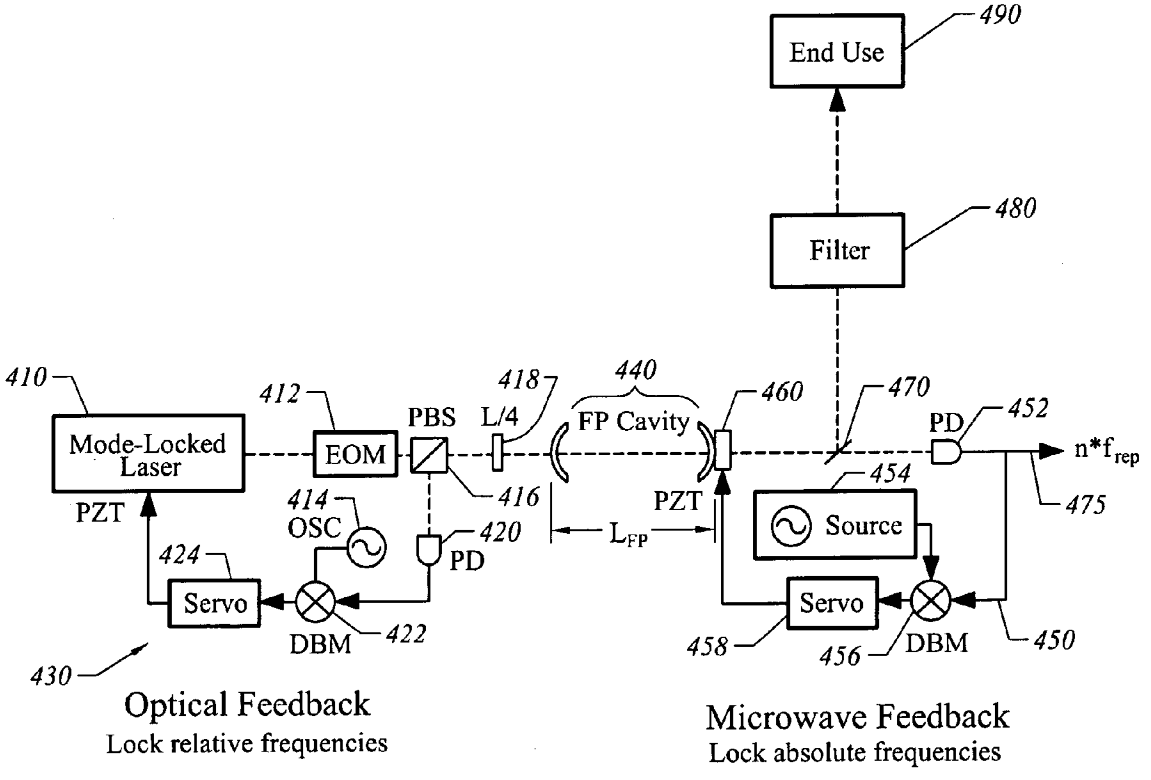
(57) **ABSTRACT**

A mode-locked laser is frequency stabilized to generate phase-locked harmonic RF signals. In one embodiment a first feedback system stabilizes a laser frequency to an optical cavity frequency of the external cavity. A second feedback system may be used to stabilize the optical cavity to a reference frequency source.



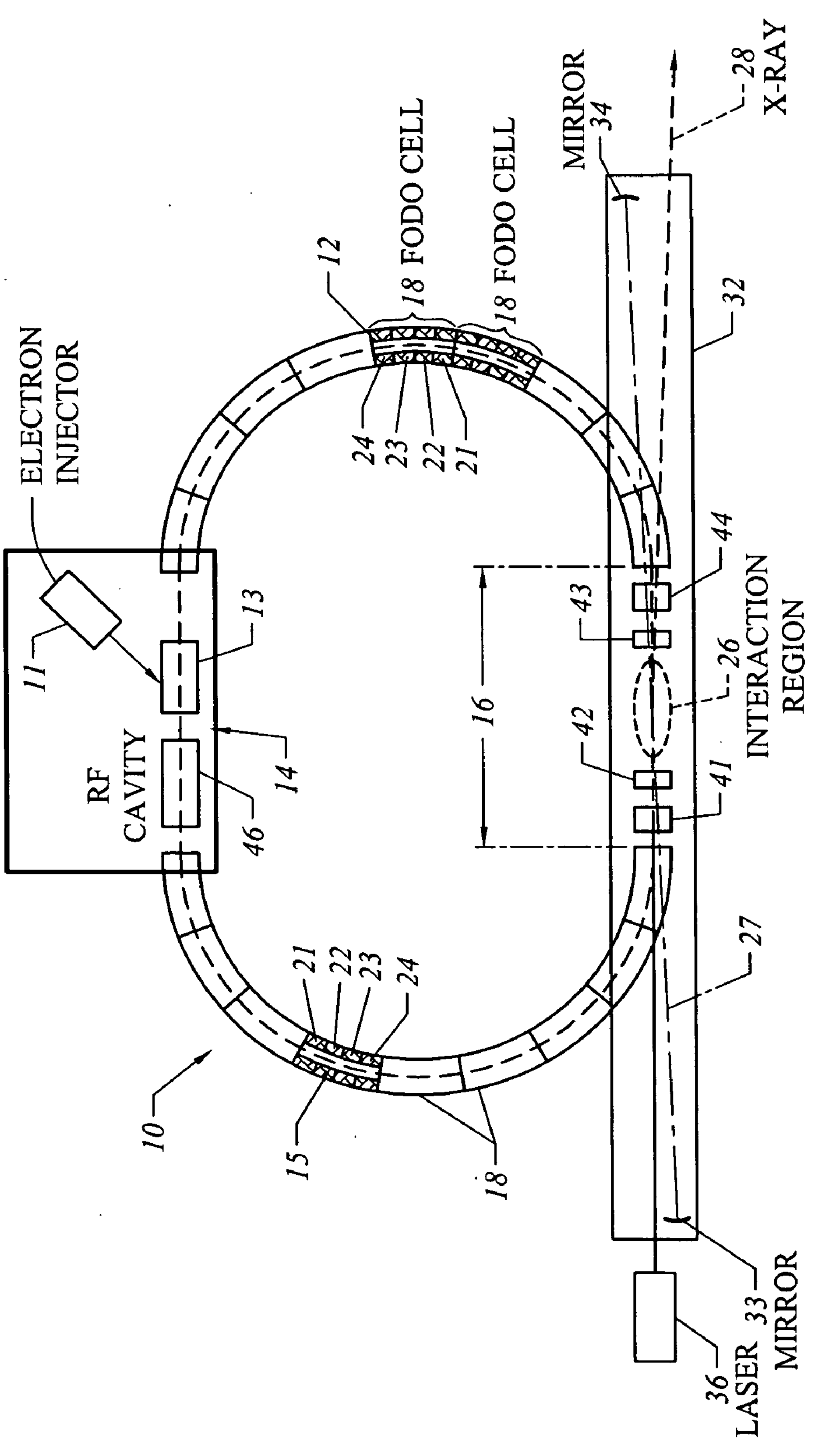


FIG. 1
(Prior Art)

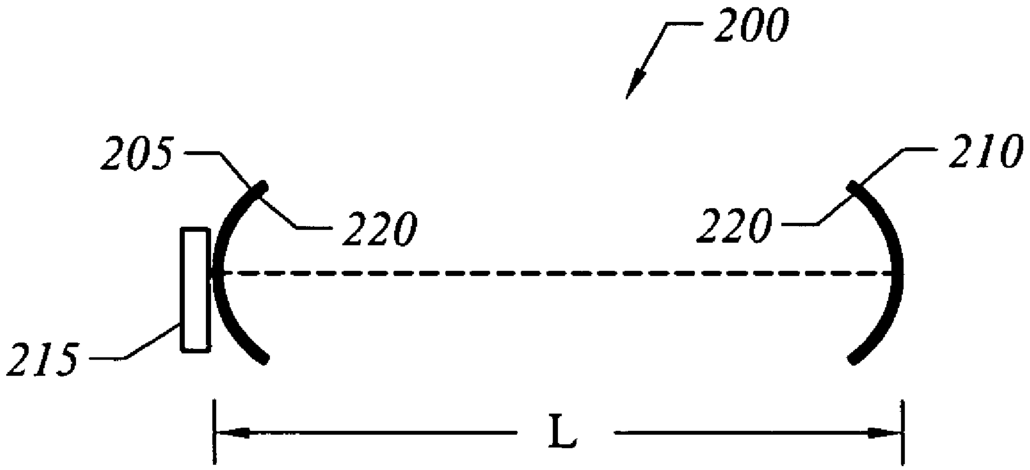


FIG. 2

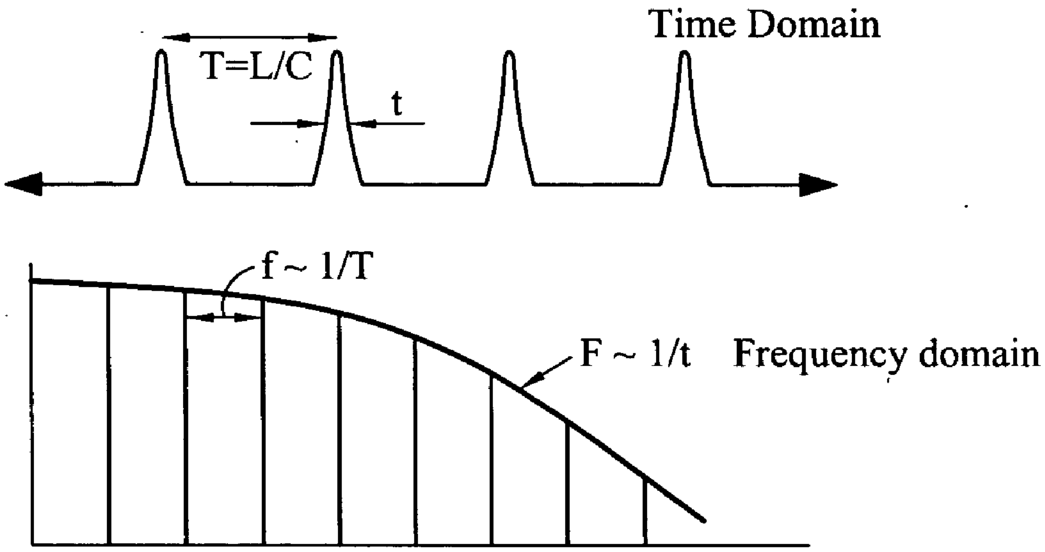


FIG. 3

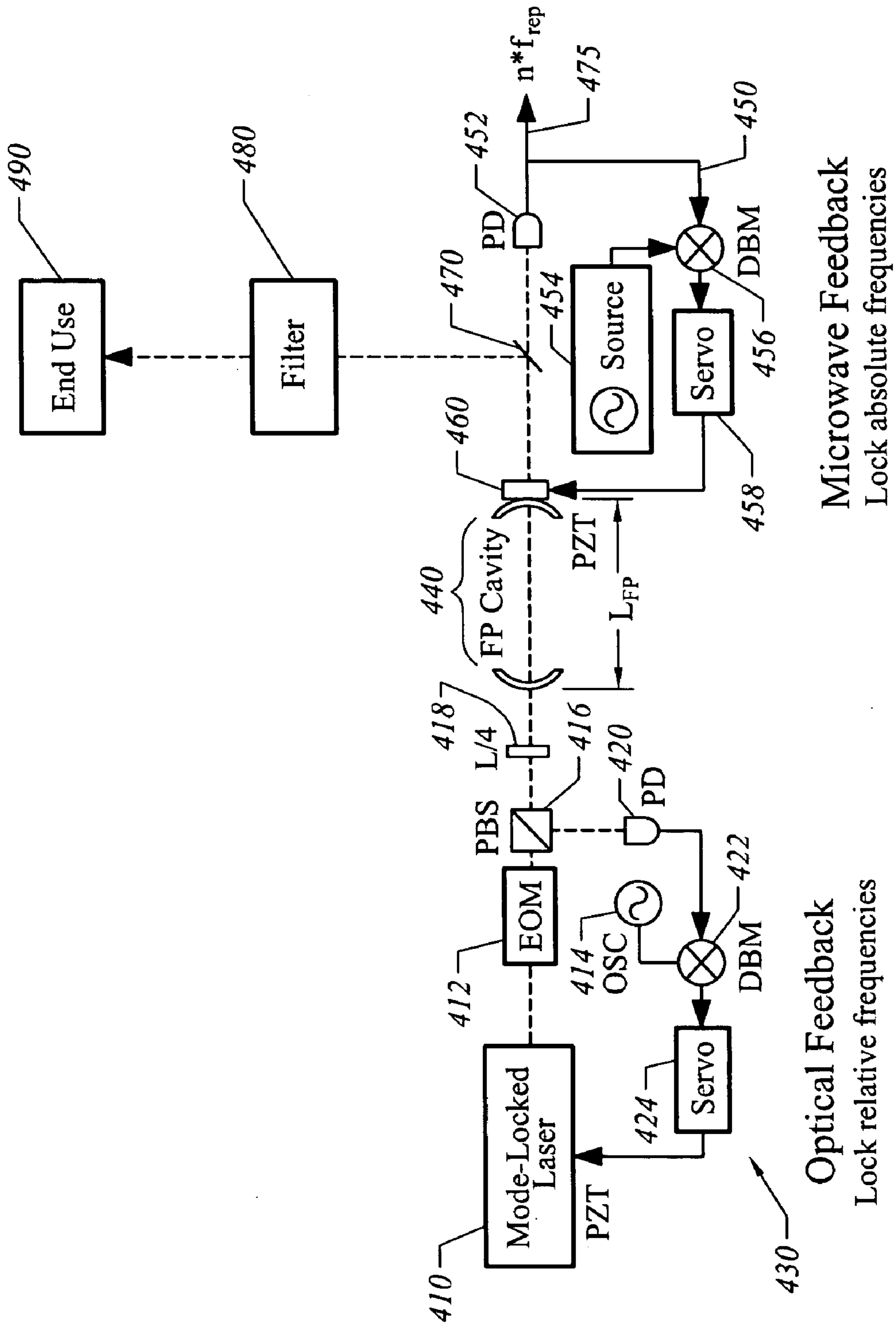

490
End Use
480
Filter
$n*f_{rep}$
475
450
452
PD
470
454
Source
DBM
Servo
456
460
458
Microwave Feedback
Lock absolute frequencies
440
FP Cavity
PZT
L_{FP}
418
L/4
416
PBS
420
PD
EOM
412
414
OSC
422
DBM
Servo
424
Mode-Locked Laser
PZT
410
430
Optical Feedback
Lock relative frequencies

FIG. 4

APPARATUS, SYSTEM, AND METHOD FOR GENERATING PHASE-LOCKED HARMONIC RF SOURCE FROM AN OPTICAL PULSE TRAIN

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of the following provisional applications: application Ser. No. 60/560,848 filed on Apr. 9, 2004, application Ser. No. 60/560,864, filed on Apr. 9, 2004; application Ser. No. 60/561,014, filed on Apr. 9, 2004; application Ser. No. 60/560,845, filed on Apr. 9, 2004; and application Ser. No. 60/560,849, filed on Apr. 9, 2004, the contents of each of which are hereby incorporated by reference.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

[0002] This invention was supported in part by a grant from the National Institutes of General Medical Sciences, National Institutes of Health, Department of Health and Human Services, grant number 4 R44 GM066511-02. The U.S. Government may have rights in this invention.

FIELD OF THE INVENTION

[0003] The present invention is generally directed towards generating pulses with a controlled frequency. More particularly, the present invention is directed towards generating a train of optical pulses having timing characteristics of interest for a variety of applications, such as driving a photocathode injector system of a Compton backscattering system.

BACKGROUND OF THE INVENTION

[0004] Synchrotron x-ray radiation sources are of interest for many different fields of science and technology. A synchrotron x-ray radiation source has a wavelength that is tunable. Intense x-ray beams with wavelengths matched to the atomic scale have opened new windows to the physical and biological world. Powerful techniques such as x-ray diffraction and scattering are further enhanced by the tunability of synchrotron radiation that can exploit the subtleties of x-ray spectroscopy.

[0005] High flux synchrotrons are typically implemented as centralized facilities that use large magnetic rings to store high-energy electron beams. As an illustrative example, a conventional third generation synchrotron may have a diameter of over 100 meters and utilize a 2-7 GeV beam, which combined with insertion devices such as undulator magnets generate 1 Angstrom wavelength x-ray radiation.

[0006] The large physical size, high cost, and complexity of conventional synchrotrons have limited their applications. For example, in many universities, hospitals, and research centers there are limitations on floor space, cost, power, and radiation levels that make a conventional synchrotron impractical as a local source of x-ray radiation. As a result, there are many medical and industrial applications that have been developed using synchrotron radiation that are not widely used because of the unavailability of a practical local source of synchrotron radiation having the necessary x-ray intensity and spectral properties.

[0007] Research in compact synchrotron x-ray sources has led to several design proposals for local x-ray sources that use the effect of Compton scattering. Compton scattering is a phenomenon of elastic scattering of photons and electrons. Since both the total energy and the momentum are conserved during the process, scattered photons with much higher energy (light with much shorter wavelength) can be obtained in this way.

[0008] One example of a Compton x-ray source is that described in U.S. Pat. No. 6,035,015, "Compton backscattered collimated x-ray source" by Ruth, et al., the contents of which are hereby incorporated by reference. **FIG. 1** shows the system disclosed in U.S. Pat. No. 6,035,015. The x-ray source includes a compact electron storage ring **10** into which an electron bunch, injected by an electron injector **11**, is introduced by a septum or kicker **13**. The compact storage ring **10** includes c-shaped metal tubes **12**, **15** facing each other to form gaps **14**, **16**. An essentially periodic sequence of identical FODO cells **18** surround the tubes **12**, **15**. As is well known, a FODO cell comprises a focusing quadrupole **21**, followed by a dipole **22**, followed by a defocusing quadrupole **23**, then followed by another dipole **24**. The magnets can be either permanent magnets (very compact, but fixed magnetic field) or electromagnetic in nature (field strength varies with external current). The FODO cells keep the electron bunch focused and bend the path so that the bunch travels around the compact storage ring and repetitively travels across the gap **16**. As an electron bunch circulates in the ring and travels across a gap **16**, it travels through an interaction region **26** where it interacts with a photon or laser pulse which travels along path **27** to generate x-rays **28** by Compton backscattering. The metal tubes may be evacuated or placed in a vacuum chamber.

[0009] In the prior art Compton x-ray source of U.S. Pat. No. 6,035,015 a pulsed laser **36** is injected into a Fabry-Perot optical resonator **32**. The resonator may comprise highly reflecting mirrors **33** and **34** spaced to yield a resonator period with a pulsed laser **36** injecting photon pulses into the resonator. At steady state, the power level of the accumulated laser or photon pulse in the resonator can be maintained because any internal loss is compensated by the sequence of synchronized input laser pulses from laser **36**. The laser pulse repetition rate is chosen to match the time it takes for the electron beam to circulate once around the ring and the time for the photon pulse to make one round trip in the optical resonator. The electron bunch and laser or photon pulses are synchronized so that the light beam pulses repeatedly collide with the electron beam at the interaction region **26**.

[0010] Special bending and focusing magnets **41**, **42**, and **43**, **44**, are provided to steer the electron bunch for interaction with the photon pulse, and to transversely focus the electron beam inside the vacuum chamber in order to overlap the electron bunch with the focused waist of the laser beam pulse. The optical resonator is slightly tilted in order not to block the x-rays **28** in the forward direction, **FIG. 3**. The FODO cells **18** and the focusing and bending magnets **41**, **42** and **43**, **44** are slotted to permit bending and passage of the laser pulses and x-ray beam into and out of the interaction region **26**. The electron beam energy and circulation frequency is maintained by a radio frequency (RF) accelerating cavity **46** as in a normal storage ring. In addition, the RF field serves as a focusing force in the longitudinal direction to confine the electron beam with a bunch length comparable to the laser pulse length.

[0011] In the prior art Compton x-ray source of U.S. Pat. No. 6,035,015 the electron energy is comparatively low, e.g., 8 MeV compared with 3 GeV electron energies in conventional large scale synchrotrons. In a storage ring with moderate energy, it is well-known that the Coulomb repulsion between the electrons constantly pushes the electrons apart in all degrees of freedom and also gives rise to the so-called intra-beam scattering effect in which electrons scatter off of each other. In prior art Compton x-ray sources the laser-electron interaction is used to cool and stabilize the electrons against intra-beam scattering. By inserting a tightly focused laser-electron interaction region **26** in the storage ring, each time the electrons lose energy to the scattered photons and are subsequently re-accelerated in the RF cavity they move closer in phase space (the space that includes information on both the position and the momentum of the electrons), i.e., the electron beam becomes "cooler" since the random thermal motion of the electrons within the beam is less. This laser cooling is more pronounced when the laser pulse inside the optical resonator is made more intense, and is used to counterbalance the natural quantum excitation and the strong intra-beam scattering effect when an intense electron beam is stored. Therefore, the electron beam can be stabilized by the repetitive laser-electron interactions, and the resulting x-ray flux is significantly enhanced.

[0012] The electron injector **11** of a Compton backscattering x-ray system may be a photocathode injector system. The timing accuracy of a photocathode injector system depends primarily on the degree of the timing control of the source of timing pulses. One technique that is used is to take an absolute reference frequency source, such as a microwave signal source, and then use frequency division or multiplication to generate control signals for a mode-locked laser to generate timing pulses at a desired frequency. However, a drawback is the accumulation of phase noise or timing jitter caused by electronic frequency multiplication or division.

[0013] Therefore, what is desired is a source of timing pulses with improved frequency control.

SUMMARY OF THE INVENTION

[0014] A mode-locked laser is used to generate a phase-locked harmonic radio frequency (RF) source. A first feedback loop is used to lock a frequency of the mode-locked laser to a cavity frequency of an optical resonator, such as a Fabry-Perot cavity. A second feedback loop may be used to adjust the cavity frequency of the optical resonator to lock to a reference frequency source. As a result, the comb of frequencies of the mode-locked laser is stabilized and may be used as one or more RF sources.

[0015] One embodiment of an apparatus comprises: an optical resonator having an adjustable resonant frequency; a mode-locked laser generating optical pulses coupled as an optical input to the optical resonator, the mode-locked laser having an adjustable cavity length whereby each frequency of a comb of frequencies may be adjusted in frequency; a first feedback system locking a frequency of the mode-locked laser to the resonant frequency of the optical resonator; and a second feedback system monitoring an optical output of the optical resonator and locking the resonant frequency to a reference frequency source.

[0016] One embodiment of a system for generating phase-locked harmonic signals includes: a Fabry-Perot cavity having a first adjustable cavity length; a mode-locked laser generating optical pulses coupled as an optical input to the Fabry-Perot cavity, the mode-locked laser having a second adjustable cavity length; a first feedback system for adjusting the second cavity length of the mode-locked laser, whereby a frequency of the mode-locked laser is locked to a cavity mode of the Fabry-Perot cavity; and a second feedback system monitoring an optical output of said Fabry-Perot cavity and adjusting the first cavity length whereby the frequency is locked to a reference frequency source.

[0017] One embodiment of a method of generating optical pulses, includes: generating mode locked laser pulses; coupling the mode-locked laser pulses to an optical resonator; tracking a frequency of the mode locked laser pulses to a resonant frequency of the optical resonator; monitoring an optical output of the optical resonator; and locking the resonant frequency of the optical resonator to a reference frequency source.

BRIEF DESCRIPTION OF THE FIGURES

[0018] The invention is more fully appreciated in connection with the following detailed description taken in conjunction with the accompanying drawings, in which:

[0019] **FIG. 1** is a block diagram of a prior art Compton x-ray source;

[0020] **FIG. 2** illustrates a mode-locked laser;

[0021] **FIG. 3** illustrates properties of a mode-locked laser; and

[0022] **FIG. 4** is a block diagram of an apparatus for generating optical pulses with controlled frequency in accordance with one embodiment of the present invention.

[0023] Like reference numerals refer to corresponding parts throughout the several views of the drawings.

DETAILED DESCRIPTION OF THE INVENTION

[0024] The present invention is generally directed towards utilizing a mode-locked laser to generate a comb of phase-locked radio frequency (RF) sources, particularly phase locked sources at microwave frequencies. It will be understood throughout the following discussion that the phase-locked RF sources may be in the form of optical domain signals or as electrical domain signals, depending upon whether the optical signals are converted into the electrical domain through an optical detector. Additionally, it will be understood throughout the following discussion that the phase-locked sources may be further frequency filtered (e.g., with an optical filter when in the optical domain or an electrical filter in the electrical domain) if desired for a particular application.

[0025] **FIG. 2** illustrates a mode-locked laser **200** with some conventional components used to generate mode-locked laser pulses (e.g., saturable absorbers and a gain media to generate light) omitted for clarity. Mode-locked laser **200** typically includes a Fabry-Perot cavity comprising a first mirror **205** and a second mirror **210**. Conventionally, one of the mirrors, such as mirror **205**, may be translatable (i.e., movable) using an actuator **215** to permit the cavity length, L, to be adjusted. Each mirror typically includes a high reflectivity coating **220**.

[0026] **FIG. 3** illustrates the output of a CW mode-locked laser **200** in the time domain and in the frequency domain. In the time domain a train of optical pulses is generated having a repetition period T=L/c, where L is the cavity length of the mode-locked laser and c is the speed of light within the cavity of the mode-locked laser. In the frequency domain a mode locked laser produces a frequency comb of equally spaced optical frequencies with the separation between frequencies inversely related to T. The comb of frequencies has an envelope where the size of the envelope is inversely proportional to the pulse width, t, of the laser pulses.

[0027] The absolute frequencies contained within the frequency comb can be completely described by two experimental parameters: the mode spacing, determined by the roundtrip time of the laser cavity of the mode-locked laser, and the roundtrip carrier envelope phase slip, which produces a single offset frequency to the entire comb. The optical frequencies in the laser comb can then be written as:.

$$v_m = mf_{rep} + f_o, \qquad \text{Equation 1}$$

[0028] where m is a large integer on the order of 10^6, f_{rep} is the pulse repetition rate of the laser, and f_0 is the offset frequency due to the pulse-to-pulse carrier phase shift. The pulse-to-pulse phase slips arise from differences is phase and group velocities inside the laser cavity. The repetition rate of a mode-locked laser equals the mode spacing to within a measurement uncertainty of 10^{-16}, and the uniformity of the comb mode spacing has been verified to a level below 10^{-17}.

[0029] A two-mirror resonator, or Fabry-Perot cavity, can support axial frequency modes, w_m given by the condition:

$$2w_m n_0 L/c - \psi_1 - \psi_2 = 2 = \pi m, \qquad \text{Equation 2}$$

[0030] where n_0 is the index of refraction of the media, L is the distance between mirrors, ψ_1 and ψ_2 and are the reflection phases of the mirrors, which in general depend on frequency ψ. For the case of multilayer dielectric mirrors, the reflection phase at normal incidence equals:

$$\psi = \pi \frac{n_0}{n_H - n_L} \frac{w - w_0}{w_0}, \qquad \text{Equation 3}$$

[0031] for $w - w_0 << w$, and $w_{0=} 2\pi c/\lambda_0$ and where the mirrors have coatings that are typically quarter-wave stacks, with layer thickness $\lambda_0/4$, containing alternating layers of high and low refractive indexes nH and nL respectively. Substituting Equation 3 into Equation 2, the frequency spacing between modes is

$$\Delta w = w_m - w_{m-1} = \frac{2\pi c}{2n_0 L + \lambda_0 n_0 / (n_H n_L)}. \qquad \text{Equation 4}$$

[0032] The reflection phases of the mirrors increase the apparent physical length of the cavity, $2n_0L$, by a value on the order of the optical wavelength, λ_0. The mirrors do not contribute any group velocity dispersion (GVD) over their central bandwidth, which is usually several percent, a value much larger than the bandwidth needed to support picosecond optical pulses (BW ~10^{-4}).

[0033] In light of the above discussion, it can be understood that a mode-locked laser tends to generate a comb of frequencies. The comb of frequencies has a center frequency of its envelope and a well-defined frequency separation that is determined by attributes of the mode-locked laser. However, frequency stabilization is required to achieve absolute frequency control of the comb frequencies and reduce residual noise.

[0034] **FIG. 4** illustrates an apparatus and system for stabilizing the output of a CW mode-locked laser **410** using an external cavity **440** that forms an optical resonator having resonant axial mode frequencies. External cavity **440** is preferably a two-mirror Fabry-Perot interferometer with a resonant frequency determined by the cavity length. The external cavity **440** has a resonant frequency selected to be near a harmonic of the laser repetition rate. Some or all of the laser output of mode-locked laser **410** is coupled to external cavity **440**. The CW mode-locked laser **410** is equipped with a high-bandwidth actuator to electronically adjust the laser cavity optical path length, for instance, a piezo-driven mirror (PZT). The laser cavity may contain another stage or other larger dynamic range adjustment such that the desired base frequency f_{rep} is controllable.

[0035] An optical feedback loop **430** locks one of the comb frequencies (e.g., a center frequency) of the mode-locked laser to that of the stable external FP cavity **440**. Optical feedback loop **430** is preferably a high bandwidth optical feedback loop that is used to track the phase or frequency deviations of the mode-locked laser **410** to that of the external cavity **440**. For example, the optical feedback loop **430** may control a piezo-electric transducer (PZT) to adjust a cavity length of mode-locked laser **410**.

[0036] An external cavity **440** that is an FP cavity is a passive device and has an inherent frequency stability. The inherent frequency stability of the external cavity **430** is leveraged by using optical feedback loop **430** to optically phase-lock mode-locked laser **410** to the cavity axial modes of cavity **440** near a resonant frequency of cavity **440**. The cavity length, L_{FP}, of external cavity **440** determines the cavity axial modes and resonant frequencies of external cavity **440**. The mode-locked laser tracks the cavity frequency of the external cavity **440** with a repetition rate f_{rep} determined by the cavity length of the external cavity. Mode-locked laser **410** resonantly couples power to the cavity such that the transmitted power contains very stable harmonics, n_{frep} (where n=1, 2, 3 . . .) with a common phase noise dictated by the passive cavity optical length stability.

[0037] In one embodiment, optical feedback loop **430** utilizes a frequency modulation (FM) sideband modulation technique. An electro-optic modulator **412** is modulated by an oscillator **414** to add an FM sideband to the optical output of mode-locked laser **410**. The FM sidebands are preferably outside the bandwidth of the external cavity **440**, for example between 1 to 20 MHz. RF oscillator (OSC) **414** drives electro-optic modulator (EOM) **412** to produce these FM sidebands. The reflected signal from the cavity input is redirected, for instance with a polarizing beam splitter (PBS)

416 and quarterwave plate (λ/4) 418, and monitored on a fast photodiode (PD) **420**. Note that PD **420** receives reflected light at the sideband frequency and may also receive a small amount of transmitted light from external cavity **440**. The photodiode signal contains phase information of the mode-locked laser **410** and external optical cavity **440** which is uncovered by demodulating the signal at the sideband value, for instance in an analog mixer (DBM) **422**. The recovered electronic signal is a suitable error signal that can be further conditioned using filters and gain stages (Servo **424**) and reapplied to the mode-locked laser PZT. The mode-locked laser **410** will then track the frequency of the cavity **440** with a performance determined largely by the actuator bandwidth. Maintaining the optical laser cavity length to within 1 part in **1012** compared to the reference cavity length is possible with commercially available PZTs and mirrors.

[**0038**] In one embodiment a second feedback loop **450** is used to control the resonant frequency (i.e., the axial mode frequencies) of external cavity **440**. This second feedback loop may be a lower bandwidth feedback system to reduce residual noise and lock an individual frequency component of the mode-locked laser frequency comb to a reference frequency source. The microwave feedback sets the cavity round-trip frequency of external cavity **440**, for instance to an RF source standard, to maintain an absolute RF reference. This results in a nearly exact comb of harmonic RF frequencies with a common-mode jitter given by the residual phase noise of the microwave feedback.

[**0039**] In one embodiment feedback loop **450** samples the optical output and compares it to a microwave reference source **454**. A portion of the output of external cavity **440** is sampled using a photodiode **452** which generates electrical domain output **475**. One of the sampled RF signal outputs (nfrep) can be compared to a microwave reference source **454** using DBM **456** to generate an error signal that is conditioned by a servo **458** and sent to a cavity piezo-mirror assembly (PZT) **460** for adjusting the cavity length of external cavity **440**. Depending on the application requirement to track an absolute frequency, one can optimize the bandwidth, and related actuator stability, of the microwave feedback system.

[**0040**] In the present invention, the first feedback loop **430** locks the mode-locked laser to within the optical bandwidth of the external cavity **440**, which reduces the free-running noise of the mode-locked laser. By reducing the free-running noise of the drive laser to within the optical bandwidth of the cavity, the laser's optical pulse train can resonantly buildup power in the external cavity. It is this circulating power which can be sampled, for instance, through an output mirror on the cavity. The entire comb of modes up to the photo-detector bandwidth will be present simultaneously in electrical output **475**. Appropriate narrowband filters may be used to select frequencies for a particular application.

[**0041**] As previously described, the present invention may also be used to generate an optical output. In an embodiment in which all of the output of mode-locked laser **410** is coupled to external cavity **440**, an optical output can be extracted from the output of external cavity **440** using, for example, an optical coupler **470**. Appropriate narrow-band filters **480** can be used to select which optical frequencies to isolate for a particular end use **490**.

[**0042**] In one embodiment the phase locked signals are used in a Compton backscattering system such as to provide a source of timing signals to a photocathode injector system. A typical photocathode injector system requires two phase-locked frequencies separated by a harmonic of **30**, for instance 100 MHz and 3000 MHz. An external cavity **440** is then built to match the repetition rate of a mode-locked laser at the base 100 MHz frequency.

[**0043**] More generally, however, the present invention may be applied to a variety of applications. In particular, the present invention may be used to provide a source of harmonically related RF frequencies in which the relative phase noise between any pair of this comb of frequencies is below 1 part in 10^{16} and the comb of frequencies is locked to an absolute value by comparing one of these frequencies to a reference source using active feedback. For example, applications exist in which the absolute frequency is less sensitive than the relative frequency stability of harmonically related RF signals. Such applications are found in pump-probe experiments (e.g. time-resolved spectroscopy) as well as conventional laser to RF synchronization (e.g. RF photoinjectors). In this case, a passive optical cavity can supply phase-locked RF sources over a comb of harmonically related frequencies. The absolute frequency can be maintained with a separate feedback loop on the passive cavity at any one frequency of this frequency comb. Since the mode-locking requires phase locking of the comb frequencies, there is no phase noise accumulation from traditional multiplication or division between any set of these frequencies.

[**0044**] Note that the pulse round-trip time in the cavity of the mode-locked laser determines the base frequency of mode-locked laser **410**, which can be in the range of 10 MHz to 10 GHz. Phase-locked harmonics of this frequency are available up to the bandwidth of an optical detector, for instance >50 GHz for photodiodes. The relative phase stability of each output frequency is determined by the optical mode-locking, which has been experimentally verified to be uniform to better than 10^{-16}. The absolute frequencies are adjusted by actively controlling the length of the cavity through a feedback loop using a reference frequency source matched to any one of the harmonic cavity frequencies. The frequency stability of the reference source is effectively transferred identically to all output frequencies of the device. Applications requiring sub-femtosecond synchronization between different harmonic frequencies thereby avoid the phase noise or timing jitter accumulation caused by electronic frequency multiplication or division.

[**0045**] An illustrative example will now be discussed. The available spectrum of frequencies is dependent on the optical pulse length and the bandwidth of the photo-detector sampling the pulse train out of the cavity. A typical 1 μm wavelength solid-state mode-locked lasers produces transform-limited ~10 picosecond FWHM pulses. This pulse length corresponds to an optical spectral width of 50 GHz. Fast photodiodes have commensurate bandwidths such that any frequency multiple of 100 MHz up to 50 GHz would be available as an output. Since the power spectrum is nearly flat over this range, the power in each mode is roughly −30 db in power from the total laser input power given a matched cavity with low internal losses. For the simplest two-mirror geometry of external cavity **440**, the cavity length would be 1.5 m long. The mirrors could be commercially available multilayer dielectrics which have a reflectivity ~0.997, corresponding to a cavity finesse of 1000 or a cavity bandwidth of 100 kHz.

[0046] In this example the frequency stabilization feedback loops would then be capable of reducing the rms frequency noise of the mode-locked laser to some fraction of the external cavity bandwidth of 100 kHz, for example 20 kHz. This low residual frequency noise assures a steady-state resonant build-up of power in the external cavity, in this case with a circulating pulse energy gain of **300**. This optical frequency stability also translates into a cavity length stability of 0.2 nm, or a frequency stability of 7 mHz at the base 100 MHz cavity mode. The residual phase noise is, however, a common mode noise on all harmonics of the frequency spectrum and sets the precision with which the cavity can be adjusted to an absolute frequency reference. The phase noise between the frequency harmonics, however, track within an experimental measurement error of 10^{-16}.

[0047] The foregoing description, for purposes of explanation, used specific nomenclature to provide a thorough understanding of the invention. However, it will be apparent to one skilled in the art that specific details are not required in order to practice the invention. Thus, the foregoing descriptions of specific embodiments of the invention are presented for purposes of illustration and description. They are not intended to be exhaustive or to limit the invention to the precise forms disclosed; obviously, many modifications and variations are possible in view of the above teachings. The embodiments were chosen and described in order to best explain the principles of the invention and its practical applications, they thereby enable others skilled in the art to best utilize the invention and various embodiments with various modifications as are suited to the particular use contemplated. It is intended that the following claims and their equivalents define the scope of the invention.

1. An apparatus for generating phase-locked harmonic signals from an optical pulse train, comprising:

an optical resonator having an adjustable resonant frequency;

a mode-locked laser generating optical pulses coupled as an optical input to said optical resonator, said mode-locked laser having an adjustable cavity length whereby each frequency of a comb of frequencies may be adjusted in frequency;

a first feedback system locking a frequency of said mode-locked laser to said resonant frequency of said optical resonator; and

a second feedback system monitoring an optical output of said optical resonator and locking said resonant frequency to a reference frequency source.

2. The apparatus of claim 1, wherein said first feedback system locks a relative frequency and said second feedback system locks an absolute frequency.

3. The apparatus of claim 1, wherein said optical resonator is a Fabry-Perot cavity and a length of said Fabry-Perot cavity is adjusted so that a resonant frequency of said Fabry-Perot cavity is locked to a harmonic of the laser repetition frequency.

4. The apparatus of claim 1, wherein a comb of frequencies of said mode-locked laser is locked to an absolute value by comparing one of the generated RF frequencies to a reference source using active feedback on the length of the external cavity.

5. The apparatus of claim 1, wherein said first feedback system comprises:

an optical sideband modulator coupled to said mode-locked laser for generating FM sideband modulated optical pulses;

an optical detector; and

a controller determining a correction to said adjustable frequency of said mode-locked laser

6. The apparatus of claim 1, wherein said second feedback system comprises:

an optical detector to detect an output of said optical resonator to generate electrical pulses;

a reference frequency source;

a comparator to compare said reference frequency source to said electrical pulses; and

a servo for adjusting a cavity length of said optical resonator in response to an error signal of said comparator.

7. The apparatus of claim 1, further comprising an optical detector for converting optical pulses from said optical resonator into electrical signals.

8. The apparatus of claim 1, wherein said apparatus is used to generate control signals for a Compton backscattering system.

9. The apparatus of claim 1, further including a narrowband filter to filter a selected frequency of the frequency comb of said mode-locked laser.

10. The apparatus of claim 9, wherein said filter filters frequencies in the optical domain.

11. The apparatus of claim 9, wherein said filter filters frequencies in the electrical domain of the output of an optical detector receiving said frequency comb of said mode-locked laser.

12. A system for generating phase-locked harmonic signals from an optical pulse train, comprising:

a Fabry-Perot cavity having a first adjustable cavity length;

a mode-locked laser generating optical pulses coupled as an optical input to said Fabry-Perot cavity, said mode-locked laser having a second adjustable cavity length;

a first feedback system for adjusting said second cavity length of said mode-locked laser, whereby a frequency of said mode-locked laser is locked to a cavity mode of said Fabry-Perot cavity; and

a second feedback system monitoring an optical output of said Fabry-Perot cavity and adjusting said first cavity length whereby said frequency is locked to a reference frequency source.

13. The system of claim 12, wherein said first feedback system comprises a FM sideband modulator for FM sideband modulating the output of said mode-locked laser, an optical detector, a demultiplexer, and a servo.

14. A method of generating phase-locked harmonic signals from an optical pulse train, comprising:

generating mode locked laser pulses;

coupling said mode-locked laser pulses to an optical resonator;

tracking a frequency of said mode locked laser pulses to a resonant frequency of said optical resonator;

monitoring an optical output of said optical resonator;

locking said resonant frequency of said optical resonator to a reference frequency source.

15. The method of claim 14, wherein said tracking comprises:

FM sideband modulating mode-locked laser pulses;

monitoring reflected and transmitted light received from an entrance mirror of said optical resonator;

generating an error signal indicative of a difference between said frequency and said resonant frequency; and

adjusting a cavity length of said mode-locked laser responsive to said error signal.

16. The method of claim 14, wherein said locking comprises:

comparing said optical output to said reference source and generating an error signal indicative of a difference between a desired absolute frequency and said frequency; and

adjusting a cavity length of said resonator responsive to said error signal.

17. The method of claim 14, further comprising:

filtering an output of said optical resonator.

18. The method of claim 14, further comprising:

utilizing an output of said optical resonator as control signal.

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