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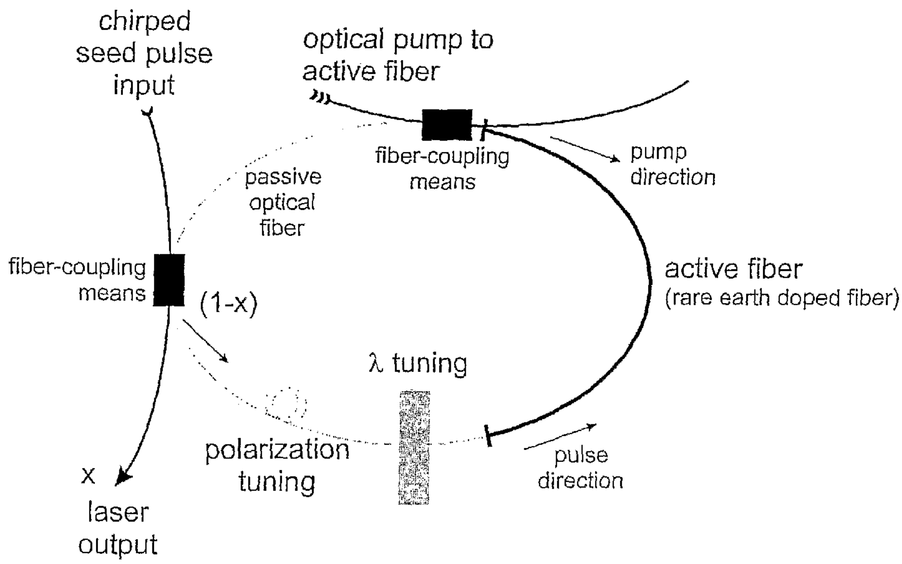
(54) Title: A CONTINUOUSLY SWEPT FREQUENCY LASER SOURCE




(57) Abstract: The present invention relates to a method for producing a substantially continuously swept frequency laser output, a substantially continuously frequency scanning laser source, a method and a system for providing a result image of a sample using the substantially continuously frequency scanning laser source. The system includes a seed pulse generator for generating a chirped seed pulse that enters an optical ring circuit comprising a frequency shifting device. For each round the light pulse travels in the ring, the frequency is shifted. The substantially continuously frequency scanning laser source is useful for any application normally incorporating a frequency scanning laser source, and in particular useful in Fourier domain optical coherence tomography.

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## A continuously swept frequency laser source

The present invention relates to a method for producing a substantially continuously swept frequency laser output, a substantially continuously frequency scanning laser source, a method and a system for providing a result image of a sample using the substantially continuously frequency scanning laser source.

The substantially continuously frequency scanning laser source is useful for any application normally incorporating a frequency scanning laser source, and in particular useful in optical low-coherence reflectometry (OLCR).

All patent and non-patent references cited in the application, or in the present application, are also hereby incorporated by reference in their entirety.

## Background

Optical low-coherence reflectometry (OLCR) is used for example for analyzing inhomogeneities in optical waveguides and optical devices. In this method light with short temporal coherence length is transmitted down the optical fibre and light resulting from the interaction with an inhomogeneity in the optical fibre is backscattered. The light is split into two arms, a sample arm and a reference arm. When the optical pathlength in the sample arm matches the time delay within the temporal coherence length in the reference arm interference occurs and the distance the light has travelled in the sample arm may be determined.

Most known devices use broadband light sources eg. superluminescent diodes, with a short temporal coherence time, and they need a scanning reference mirror to record the depth resolved backscattered signal. In other systems a tunable laser is used as the light source, whereby, instead of moving the mirror, the wavelength of the laser can be varied to record the backscattered signal. This principle is discussed in Haberland, U.H.P. et al., "Chirp Optical Coherence Tomography of Layered Scattering Media" as well as in US 5,956,355 (Swanson et al.). The method is often referred to as coherent optical frequency modulated continuous wave (FMCW) reflectometry.

OLCR can be extended through the use of polarized light. The light field towards the reference and sample is then polarized. After combining the light field reflected from the reference and the sample, the combined light field is split up again into two new light fields with perpendicular polarization states. Through this method the birefringent properties of the sample can be investigated in addition to the information obtainable with ordinary OLCR adding to the systems ability to discriminate between certain types of materials within the sample. This method also applies to OCT often referred to as polarization sensitive OCT (PS-OCT), as well as coherent optical FMCW reflectometry.

Optical low-coherence reflectometry is also used in the imaging of 2-dimensional and 3 dimensional structures, eg. biological tissues, in this respect often referred to as optical coherence tomography (OCT). OCT can be used to perform high-resolution cross-sectional *in vivo* and *in situ* imaging of microstructures, such as in transparent as well as non-transparent biological tissue or other absorbing and/or random media in generel. There are a number of applications for OCT, such as non-invasive medical diagnostic tests also called optical biopsies. For example cancer tissue and healthy tissue can be distinguished by means of different optical properties. Coherent optical FMCW reflectometry also applies to the above-mentioned cases.

A laser type used for generating a sweep of the optical frequency in time, is the so-called frequency shifted feedback (FSF) laser (see for example Yoshiwara A and Tsuchida H "Chirped-comb generation in frequency-shifted feedback laser diodes with a large frequency shift" Optics Communication 155 (1998) 51-54). The output of this laser is a chirped frequency comb. Due to the limited sweeping range of the FSF laser, it is not possible to obtain the resolution of interest in OCT systems. In fact, the effectively scanned bandwidth (of the optical spectrum) that may be utilized is significantly less than the maximum bandwidth, which is determined by the choice of gain-medium.

In Shimizu K et al. "Frequency translation of light waves by propagation around an optical ring circuit containing a frequency shifter: I Experiment" Applied Optics Vol. 32, No. 33 20 November 1993 a laser is suggested wherein a frequency shifter is incorporated into an optical ring circuit for providing a pulsetrain of frequency translated pulses. The laser is described as useful in light wave communication and frequency-division-multiplexing (FDM) transmission as well as in OLCR, the latter on the condition that the time width of one step is adjusted so that it is shorter than the round-trip time for the distance corresponding to the spatial resolution.

Because the spatial resolution of interest in OCT is only a few micrometers, this condition imposes a fundamental problem in case the laser described in Shimizu et al. should be applied in OCT.

## Summary of invention

The present invention relates to a method for providing a smooth continuously swept frequency laser output suitable for use in for example OCT.

Accordingly, the present invention relates to a method for producing a substantially continuously swept frequency laser source output, said method comprising

a) providing a frequency chirped seed pulse having a chirp rate df/dt, said chirp rate df/dt being different from zero, and providing

- at least one optical ring circuit, said at least one optical ring circuit comprising a frequency shifting device, at least two active gain media arranged in parallel, and optionally an optical delay line, or

- at least two separate optical ring circuits arranged in series, said at least two optical ring circuits comprising a frequency shifting device, at least one active gain medium, and optionally an optical delay line,

b) injecting at least a fraction of said chirped seed pulse to at least one optical ring circuit,

c) shifting frequency of said fraction of said chirped pulse in the optical ring circuit, obtaining a frequency shifted chirped pulse,

d) amplifying the chirped pulse in the optical ring circuit, obtaining an amplified pulse,

e) extracting a fraction x of the amplified frequency shifted chirped pulse as laser output, and reinjecting a fraction y of the amplified frequency shifted chirped pulse into at least one optical ring circuit,

f) optionally repeating the steps c) to e) at least once, whereby the fraction y of the amplified frequency shifted chirped pulse is regulated in step d),

g) obtaining a substantially continuously swept frequency laser source output with substantially smooth frequency sweep, and

h) optionally repeating the steps a) to g) at least once obtaining a series of substantially continuously swept frequency laser source output each with substantially smooth frequency sweep.

By providing at least two optical ring circuits arranged in series and/or providing at least two active gain media in an optical ring circuit, it is possible to increase the effective bandwidth of the laser source.

In another aspect, the invention relates to a method for producing a substantially continuously swept frequency laser source output, said method comprising

a) providing a frequency chirped seed pulse having a chirp rate df/dt, said chirp rate df/dt being different from zero, and providing at least one optical ring circuit, said at least one optical ring circuit comprising a frequency shifting device, at least one active fibre, and optionally an optical delay line, wherein the at least one active fibre is pumped optically by at least two laser diodes, one of said two laser diodes having a first wavelength and the other of said two laser diodes having a second wavelength,

b) injecting at least a fraction of said chirped seed pulse to at least one optical ring circuit,

c) shifting frequency of said fraction of said chirped pulse in the optical ring circuit, obtaining a frequency shifted chirped pulse,

d) amplifying the chirped pulse in the optical ring circuit, obtaining an amplified pulse,

e) extracting a fraction x of the amplified frequency shifted chirped pulse as laser output, and reinjecting a fraction y of the amplified frequency shifted chirped pulse into at least one optical ring circuit,

f) optionally repeating the steps c) to e) at least once, whereby the fraction y of the amplified frequency shifted chirped pulse is regulated in step d),

g) obtaining a substantially continuously swept frequency laser source output with substantially smooth frequency sweep, and

h) optionally repeating the steps a) to g) at least once obtaining a series of substantially continuously swept frequency laser source output each with substantially smooth frequency sweep.

Furthermore, the invention relates to a system capable of providing a smooth continuously swept frequency laser output, namely a substantially continuously frequency scanning laser source comprising

a) a light source capable of providing a frequency chirped seed pulse having a chirp rate df/dt, said chirp rate df/dt being different from zero,

b) coupling means for injecting at least a fraction of said chirped seed pulse into at least one optical ring circuit,

c) at least one optical ring circuit, said at least one optical ring circuit comprising a frequency shifting device, at least two active gain media arranged in parallel, and optionally an optical delay line, or at least two separate optical ring circuits arranged in series, said at least two optical ring circuits comprising a frequency shifting device, at least one active gain medium, and optionally an optical delay line,

d) out-put coupling means for extracting a fraction x of the frequency shifted chirped pulse as laser output.

In another aspect, the invention relates to a system capable of providing a smooth continuously swept frequency laser output, namely a substantially continuously frequency scanning laser source comprising

a) a light source capable of providing a frequency chirped seed pulse having a chirp rate df/dt, said chirp rate df/dt being different from zero,

b) coupling means for injecting at least a fraction of said chirped seed pulse into at least one optical ring circuit,

c) at least one optical ring circuit, said at least one optical ring circuit comprising a frequency shifting device, at least one active fibre, and optionally an optical delay line, at least two laser diodes, one of said two laser diodes having a first wavelength and the other of said two laser diodes having a second wavelength, said laser diodes being arranged so that the at least one active fibre is pumped optically by at least two laser diodes,

d) out-put coupling means for extracting a fraction x of the frequency shifted chirped pulse as laser output.

In another aspect the invention relates to a method for producing a substantially continuously swept frequency laser source output, said method comprising

a) providing a frequency chirped seed pulse having a chirp rate df/dt, said chirp rate df/dt being different from zero, and providing

- at least one optical ring circuit, said at least one optical ring circuit comprising a frequency shifting device, at least one active gain media, and optionally an optical delay line, wherein an isolator is arranged between a seed pulse generator and the optical ring circuit,

b) injecting at least a fraction of said chirped seed pulse to at least one optical ring circuit,

c) shifting frequency of said fraction of said chirped pulse in the optical ring circuit, obtaining a frequency shifted chirped pulse,

d) amplifying the chirped pulse in the optical ring circuit, obtaining an amplified pulse,

e) extracting a fraction x of the amplified frequency shifted chirped pulse as laser output, and reinjecting a fraction y of the amplified frequency shifted chirped pulse into at least one optical ring circuit,

f) optionally repeating the steps c) to e) at least once, whereby the fraction y of the amplified frequency shifted chirped pulse is regulated in step d),

g) obtaining a substantially continuously swept frequency laser source output with substantially smooth frequency sweep, and

h) optionally repeating the steps a) to g) at least once obtaining a series of substantially continuously swept frequency laser source output each with substantially smooth frequency sweep.

By introducing an isolator instability of the seed pulse generator is avoided. Accordingly, the invention further relates to a substantially continuously frequency scanning laser source comprising

a) a light source capable of providing a frequency chirped seed pulse having a chirp rate df/dt, said chirp rate df/dt being different from zero,

b) coupling means for injecting at least a fraction of said chirped seed pulse into at least one optical ring circuit,

c) at least one optical ring circuit, said at least one optical ring circuit comprising a frequency shifting device, at least one active gain media, and optionally an optical delay line, wherein an isolator is arranged between the light source and the optical ring circuit,

d) out-put coupling means for extracting a fraction x of the frequency shifted chirped pulse as laser output.

In another aspect the invention relates to a method for producing a substantially continuously swept frequency laser source output, said method comprising

a) providing a frequency chirped seed pulse having a chirp rate df/dt, said chirp rate df/dt being different from zero, and providing

- at least one optical ring circuit, said at least one optical ring circuit comprising a frequency shifting device, at least one active gain media, an amplification means and optionally an optical delay line,

b) seeding the amplifier with CW signal prior to the frequency scanning thereby bringing the amplifier into its saturated gain regime.

c) injecting at least a fraction of said chirped seed pulse to at least one optical ring circuit,

d) shifting frequency of said fraction of said chirped pulse in the optical ring circuit, obtaining a frequency shifted chirped pulse,

e) amplifying the chirped pulse in the optical ring circuit, obtaining an amplified pulse,

f) extracting a fraction x of the amplified frequency shifted chirped pulse as laser output, and reinjecting a fraction y of the amplified frequency shifted chirped pulse into at least one optical ring circuit,

g) optionally repeating the steps c) to f) at least once, whereby the fraction y of the amplified frequency shifted chirped pulse is regulated in step d),

h) obtaining a substantially continuously swept frequency laser source output with substantially smooth frequency sweep, and

i) optionally repeating the steps b) to h) at least once obtaining a series of substantially continuously swept frequency laser source output each with substantially smooth frequency sweep.

In yet another aspect the invention relates to a method for producing a substantially continuously swept frequency laser source output, said method comprising

a) providing a frequency chirped seed pulse having a chirp rate df/dt, said chirp rate df/dt being different from zero, and providing

- at least one optical ring circuit, said at least one optical ring circuit comprising a frequency shifting device, at least one active gain media, an amplification means, a dispersive element and optionally an optical delay line,

b) injecting at least a fraction of said chirped seed pulse to at least one optical ring circuit,

c) shifting frequency of said fraction of said chirped pulse in the optical ring circuit, obtaining a frequency shifted chirped pulse,

d) amplifying the chirped pulse in the optical ring circuit, obtaining an amplified pulse,

e) extracting a fraction x of the amplified frequency shifted chirped pulse as laser output, and reinjecting a fraction y of the amplified frequency shifted chirped pulse into at least one optical ring circuit,

f) optionally repeating the steps b) to e) at least once, whereby the fraction y of the amplified frequency shifted chirped pulse is regulated in step d),

g) obtaining a substantially continuously swept frequency laser source output with substantially smooth frequency sweep, and

h) optionally repeating the steps a) to h) at least once obtaining a series of substantially continuously swept frequency laser source output each with substantially smooth frequency sweep.

By introducing a dispersive element into the optical ring circuit wavelength dependent deflection of the frequency shifted chirped pulse is reduced. Accordingly, the invention further relates to a substantially continuously frequency scanning laser source comprising

a) a light source capable of providing a frequency chirped seed pulse having a chirp rate df/dt, said chirp rate df/dt being different from zero,

b) coupling means for injecting at least a fraction of said chirped seed pulse into at least one optical ring circuit,

c) at least one optical ring circuit, said at least one optical ring circuit comprising a frequency shifting device, at least one active gain media, an amplification means, a dispersive element and optionally an optical delay line,

d) out-put coupling means for extracting a fraction x of the frequency shifted chirped pulse as laser output.

In another aspect the invention relates to a method for producing a substantially continuously swept frequency laser source output, said method comprising

a) providing a frequency chirped seed pulse having a chirp rate df/dt, said chirp rate df/dt being different from zero, and providing

- at least one optical ring circuit, said at least one optical ring circuit comprising a frequency shifting device, at least one active gain media, an amplification means, and optionally an optical delay line,

b) injecting at least a fraction of said chirped seed pulse to at least one optical ring circuit,

c) shifting frequency of said fraction of said chirped pulse in the optical ring circuit, obtaining a frequency shifted chirped pulse,

d) amplifying the chirped pulse in the optical ring circuit, obtaining an amplified pulse,

e) extracting a fraction x of the amplified frequency shifted chirped pulse as laser output, and reinjecting a fraction y of the amplified frequency shifted chirped pulse into at least one optical ring circuit,

f) amplifying the fraction x and/or the fraction y from step e),

g) optionally repeating the steps c) to f) at least once, whereby the fraction y of the amplified frequency shifted chirped pulse is regulated in step d),

h) obtaining a substantially continuously swept frequency laser source output with substantially smooth frequency sweep, and

i) optionally repeating the steps b) to h) at least once obtaining a series of substantially continuously swept frequency laser source output each with substantially smooth frequency sweep.

By introducing an amplifier after the optical ring circuit it is possible to adjust the output power from the ring circuit. Accordingly, the invention further relates to a substantially continuously frequency scanning laser source comprising

a) a light source capable of providing a frequency chirped seed pulse having a chirp rate df/dt, said chirp rate df/dt being different from zero,

b) coupling means for injecting at least a fraction of said chirped seed pulse into at least one optical ring circuit,

c) at least one optical ring circuit, said at least one optical ring circuit comprising a frequency shifting device, at least one active gain media, and optionally an optical delay line, wherein an isolator is arranged between the light source and the optical ring circuit,

d) out-put coupling means for extracting a fraction x of the frequency shifted chirped pulse as laser output, and

e) an amplifier for amplifying the laser output.

Also, the invention relates to an apparatus for optical coherence reflectometry comprising

- a frequency scanning laser source as defined above for providing a light signal

- splitting means for dividing said light signal into a first light field and a second light field,

- means for directing the first light field to a sample, and means for directing a first reflected light field from the sample, to a combining means,

- means for directing the second light field to a reference path comprising a reflecting means, and means for directing a second reflected light field from the reference path to the combining means,

- combining means for receiving said first reflected light field and said second reflected light field to generate a combined light signal, and

- at least one detecting means for detecting the combined light signal and outputting detection signals.

The system may for example be used in a method for providing a result image of a sample comprising

- establishing a frequency scanning laser source as defined above for providing a light signal,

- splitting said light signal into a first light field and a second light field,

- directing the first light field to a sample, and the second light field to a reference path,

- receiving the first reflected light field from the sample, and the second reflected light field from the reference path,

- combining said first reflected light field and said second reflected light field to generate a combined light signal,

- detecting the combined light signal obtaining detection signals, and

- processing the detection signals obtaining the result image of the sample.

**Description of Drawings**

Fig. 1. Sketch of the heterodyne mixing using a scanning frequency source.

Fig. 2. Laser output frequency as a function of time. Note that the chirp is repeated to form a saw-tooth shape.

Fig. 3. Laser output frequency as a function of time with chirp in the injected pulse.

Fig. 4 shows a schematic realization of scanning ring laser with one optical ring circuit.

Fig. 5 shows a schematic realization of another embodiment of the scanning ring laser of Fig. 4, namely a scanning ring laser with two optical ring circuits.

Fig. 6 shows a schematic realization of another embodiment of the scanning ring laser of Fig. 4, namely a scanning ring laser with 1 - n gain media arranged in parallel in the optical ring circuit.

**Definitions**

Chirped pulse: a frequency shifted pulse

Fraction x of the laser output: The fraction of the laser output that is used directly or indirectly as laser source output.

Fraction y of the laser output: The fraction to be reinjected into an optical ring circuit for another round of frequency shifting and amplification, corresponding to fraction 1-x.

Frequency shifting device is used synonymously with frequency tuning device or frequency tuning element.

Laser output: Laser output is used to denote the output from an optical ring circuit.

Optical ring circuit is also denoted cavity in the present context.

Seed pulse: a pulse injected into the optical ring circuit only once per total scanning of entire gain bandwidth.

Substantially continuously swept frequency: means that the sweeping is conducted in order to obtain a mode-hop free tuning.

**Detailed description of the invention**

As described above the present invention relates to a method and a system for providing a substantially continuous swept frequency laser source output. Thereby the method and the system is especially suitable for providing a wavelength variation over a sufficient wavelength difference ($\Delta\lambda$) to establish a high axial spatial resolution in the depth sizes (a few micrometers) necessary in optical coherence tomography used for a variety of medical purposes.

Furthermore, the laser source according to the invention preferably is scanning the entire bandwidth rapidly, has a large bandwidth, operates with mode-hop free tuning and may be easily fiber coupled.

This is achieved by incorporating a frequency shifting element inside an optical ring circuit and injecting a seed pulse into the optical ring circuit, wherein said seed pulse itself has an internal chirp.

Every round-trip the pulse travels around the optical ring circuit, it receives a frequency increase or a frequency decrease (df). The output of the laser source (fraction x of the pulse) is thereby a pulse train having a repetition rate corresponding to the round trip time of the ring. As opposed to the prior art methods there will be substantially no discontinuities in frequency space since the internal chirp of the seed pulse and the frequency shift in each roundtrip may be adjusted to each other, so that the initial frequency of one pulse corresponds substantially to the final frequency of the former pulse. Preferably there are no discontinuities in the frequency space, since such discontinuities will appear as mode-hops. In other words by the present invention it is possible to obtain a pulse train arising from one injected chirped seed pulse wherein said pulse train has a total wavelength difference $\Delta\lambda_{total}$ that corresponds substantially to the sum of wavelength differences ($\Delta\lambda_{seed\ pulse,}$) of each pulse included in the pulse train. The higher $\Delta\lambda_{total}$ the higher axial spatial resolution and thereby the more relevant for optical coherence tomography.

The scanning speed may be changed by changing (one or more):

the frequency increase/decrease by the frequency shifter
the round trip time (cavity length)
the bandwidth of the gain medium(s)

In one embodiment the pulse may sweep the gain bandwidth in less than 10 msec, whereby the scanning speed of an OCT system incorporating the method and the system according to the invention is equivalent to the scanning speed of the delay line in conventional OCT.

In the following the various features of the method and laser source according to the invention is described in more detail.

**Chirp rate**

An important feature of the present invention is the provision of a frequency chirped seed pulse having a chirp rate df/dt, said chirp rate df/dt being different from zero.

The chirp of the seed pulse in step a) is preferably a linear chirp, so that the frequency preferably rises in a continuously linear fashion. Accordingly, the frequency chirp of the seed pulse should preferably be generated to an ideal linear ramp to insure generation of a plurality of linear chirps, each with a fixed rate of change of frequency per second regardless of temperature variations and regardless of changes in rate of chirps per second.

However, the invention may also employ sources for generating the chirped seed pulse, wherein the chirp rate df/dt deviates from linearity. In such case the non-linearity of the chirp rate is preferably compensated for or corrected elsewhere in the method and system. The person skilled in the art knows of methods for linearizing chirps generated by non-linear sources. For example US 5,376,938 describes measuring the non-linearity of each individual source to determine the deviation in its output frequency from an ideal linear rate of change of frequency as each chirp is generated. The deviation between the actual generated frequency at each instant of a chirp and the ideal linear ramp is converted to a correction factor.

In a preferred embodiment the chirp generator is adjusted to generate a ramp signal which linearly ramps up in frequency at a rate needed to establish the desired rate of change in frequency of the chirp.

The chirp rate df/dt is preferably adjusted to the frequency shifting conducted when travelling in the optical ring circuit. Accordingly, the chirp rate df/dt preferably equals the frequency shift per round trip time to ensure that the beginning wavelength of one output substantially corresponds to the final wavelength of the immediate former output in order to provide the substantial continuity of the total output.

In a preferred embodiment the chirp rate df/dt is in the range of from 25 MHz – 10 GHz, such as from 25 – 1000 MHz, such as from 25 – 500 MHz, such as from 50 – 500 MHz, such as from 50 - 250 MHz, such as from100 - 200 MHz, per round trip time. The higher the chirp rate the fewer pulses are necessary in the pulse train to obtain a predetermined frequency scan, thereby increasing the overall speed of a frequency scan.

The frequency chirped seed pulse may be provided from any suitable chirped seed pulse generating means. Examples of such are: a tunable (grating, thermal) laser diode seed source, diode pumped solid state laser seed source, and frequency swept ASE source.

The chirp generator may be regulated to produce the chirped seed pulse at a predetermined continuous fashion, wherein the chirped seed pulse is provided at a continuous frequency. In another embodiment the chirped seed pulse is only triggered on request from another part of the system when needed in the system.

In one embodiment the seed pulse source may be adjustable, whereby it is possible to switch the method and the system from a rapid-sweep mode (large $\delta\omega$) to slow scan mode (small $\delta\omega$), or more preferably also to tune therebetween.

The wavelength of the chirped seed pulse is preferably selected within the optical bandwidth of at least one of the gain-mediums used.

**Optical ring circuit**

The laser source according to the invention comprises at least one optical ring circuit, the optical ring circuit being composed as a fiber ring or a free space ring or a combination thereof.

In its most fundamental configuration, an optical ring circuit comprises a frequency shifting device, an active gain medium, and optionally an optical delay line, that is positioned in any configuration in relation to each.

The total length of the optical ring circuit is adjusted to the application of the laser source. It is preferred that the length of the optical ring circuit is adjusted to ensure a travelling time in the optical circuit that is matched to or longer than the corresponding pulse width.

The shorter the ring, the faster the total frequency scan can be. On the other hand the shorter the pulse the higher the risk that the chirp of the seed pulse is non-linear. So the length of the optical ring circuit is a balance between the two extremes. In most applications the pulse width is in the range of from 25-500 ns, such as in the range of from 50-500 ns, such as in the range of from 50-250 ns.

As discussed above, the invention includes in one aspect at least two optical ring circuits, such as two optical circuits arranged in series, such as three optical circuits arranged in series, such as four optical circuits arranged in series. Each optical ring circuit comprises at least one active gain medium. The effective bandwidth of a gain medium in one optical ring circuit is preferably different from the effective bandwidth of a gain medium of the next optical ring circuit, more preferably different and over-lapping.

In one embodiment an isolator is incorporated between the seed pulse generator and the optical ring circuit to avoid instability in the seed laser.

**Active gain medium**

As discussed above a large bandwidth of the gain-medium(s) of the optical ring circuit is an advantage since it allows a large scanning range of the frequency, and thereby optimises the axial spatial resolution when the laser source is used for example in OCT.

The active gain-medium is selected from any suitable gain-medium known to the person skilled in the art. The active gain medium may thus be selected from a discrete crystal or multiple crystals of gain medium, or an active fiber, or multiple different active fibers having compositionally tuned gain bandwidths so as to increase the effective bandwidth. Furthermore, the optical ring circuit(s) may include a combination of two or more of the gain-mediums suggested above.

The use of fibers with doped cores has become a useful tool in many applications. Doping these fibres with different ions produces optical gain for light amplification in the fiber cores at various wavelength ranges. In one embodiment the active gain medium is an active fiber, such as a rare earth doped fiber, such as a fiber selected from a Neodymium doped fiber, an Ytterbium doped fiber, an Erbium doped fiber, or a Thulium doped fiber or combinations thereof. Optical gain for a signal propagating in the doped fiber core occurs when population inversion in the inner core material is induced by the absorption of pump light.

In a preferred embodiment the active fiber is a rare earth doped photonic crystal fiber.

The bandwidth area of the active gain medium is selected according to the application of the laser source. The wavelengths scanned are adjusted to the purpose of the analysis performed with the apparatus. The wavelengths are mostly selected in the range from 500 nm to 2000 nm. For non-transparent solid tissue the wavelength is normally selected in the range from 1100 nm to 2000 nm. For retinal examinations the wavelength is mostly selected in the range from 600 nm to 1300 nm.

In one aspect the at least one optical ring circuit comprises at least two different gain media arranged in parallel in the optical ring circuit. Thereby it may be possible to increase the effective bandwidth of the laser source when the at least two different gain media has different, preferably over-lapping, effective bandwidths. The optical ring circuit may be provided with switching means capable of switching from one gain medium to the other gain medium when the wavelength increase requires shift of gain medium.

In another aspect the laser source is provided with at least two separate optical ring circuits being arranged in series, and the gain medium of one optical ring circuit is different from the gain medium of another ring circuit whereby the effective bandwidth of the laser source may be increased as discussed above. In this configuration the output fraction x from one optical ring circuit may be the fraction injected into the next optical ring circuit in the series of optical ring circuits.

**Pumping**

The active fiber is pumped optically to its excited state by using a pump light. The pump light may be selected from any suitable laser light sources, such as by at least one laser diode, using at least one frequency resonantly absorbed in the fiber. In one aspect of the invention, the active gain medium may be pumped optically by two laser diodes, one of said two laser diodes having a first wavelength and the other of said two laser diodes having a second wavelength. In one embodiment it is preferred that the first wavelength is different from the second wavelength in order to increase the gain bandwidth. However it may also be preferred to use a first wavelength and a second wavelength, wherein the two wavelengths are at least substantially identical to increase the end-pump from each end in order to achieve homogeneous excitation of fiber with length.

By end pumping the fiber is not weakened by cutting the cladding. Preferably, diffraction limited laser diodes are used to achieve efficient diode to fiber coupling. Pump light is injected into the fiber core by proximity coupling into the polished face of the fiber, or by means of focusing optics between the laser aperture and the input face of the fiber.

In a preferred embodiment the active fiber is a double-clad fiber, i.e. an active fiber configuration with a double cladded structure. The double cladded structure consists of a single mode fiber core, an inner cladding and an outer cladding. The refractive index is highest in the core and lowest in the outer cladding, so that both the fiber core and the inner cladding function as optical waveguides. The important feature of the double cladded structure is that light can be injected into the inner cladding where it propagates until it is absorbed by the active dopant in the fiber core.

The index difference between the inner cladding and the outer cladding is often made relatively large, so that the effective numerical aperture of the inner cladding waveguide is very large. The large diameter and numerical aperture of the inner cladding waveguide make it possible to effeciently couple spatially incoherent emission from high power, large aperture, broad area laser diodes or laser diode arrays. One advantage of the double-clad fiber is thus, that it allows the use of low beam quality pump light of low costs.

In a preferred embodiment the double-clad fiber is pumped in a V-groove configuration injecting the light through the side of the fiber as described in US 5,854,865.

In a preferred embodiment the core of the active fiber is pumped directly by making use of the feedback diode laser system in patent no. PCT/DK01/00576 and WO 98/56087, whereby any amplified spontaneous emission may be minimised. Also by pumping directly into the core, the length of the active fiber may be reduced.

When arranging the optical ring circuit in series or having active gain-medium arranged in parallel in each optical ring circuit, it is understood by the present invention, that the active gain-medium may be different in each part of the series. Thereby it is possible to optimize the method and the system towards any necessary bandwidth when producing the continuously swept frequency laser source output.

**Amplification**

The optical ring circuit includes at least one amplification means for amplifying the pulse travelling in the optical ring circuit. The amplification means is for example the active gain-medium. The amplification is conducted in order to regulate the fraction y of the original pulse re-injected into the system for each round-trip. The amplification should preferably at least compensate for the fraction x extracted from the optical ring circuit in each round trip. Furthermore, the amplification preferably also compensates for any optical loss occurring in the optical ring circuit. Thereby there is no net depletion of the pulse nor any excessive gain. It may however be relevant to increase the gain in order to increase intensity of the pulse.

The amplification means may be positioned anywhere in the optical ring circuit. In one embodiment the pulse is first subjected to a frequency offset (either increase or decrease) and then subjected to amplification for example through the active gain-medium. In another embodiment the amplification is conducted before offsetting the frequency.

In a preferred embodiment a dispersive element may be arranged after the frequency shifting means. The angle of the light leaving the frequency shifting means will gradually change due to the shift in optical frequency. Due to the changes of the angle, the coupling of the frequency shifted chirped pulse to the ring will be less effective. This may be compensated at least partially by the dispersive element. Any suitable dispersive element may be used, such as a grating or a prism.

**Frequency shifting device**

The frequency shifting device providing the offset may be any suitable tuning element capable of shifting the frequency. In a preferred embodiment the frequency shifting device is selected from an acousto-optic device or an electro-optic device.

A standard acousto-optical modulator operating as a frequency shifter has a limited optical bandwidth for a fixed input and output angle. There are several alternatives to an acousto-optical modulator to perform such frequency shifting, such as electro-optical modulators.

The output frequency rate is precisely incremented by an amount equal to the frequency shift imposed by the frequency shifter every time the light encircles around the ring. The frequency shifting device is preferably capable of providing a frequency offset $f_{offset}$ as the chirp in the chirped seed pulse. Accordingly, the frequency offset is preferably in the range of from 25 MHz – 10 GHz, such as from 25 – 1000 MHz, such as from 25 – 500 MHz, such as from 50 – 500 MHz, such as from 50 - 250 MHz, such as from 100 - 200 MHz, per round trip in the optical ring.

**Optical delay**

The optical delay line is preferably incorporated into the optical ring circuit for adjusting the length of the optical ring circuit. Thus, the optical delay line is a path length compensating element, including passive and/or active elements, adjusting the total optical ring path length as discussed above. The optical delay line may be selected from any suitable means, such as selected from a passive fiber, free space propagation, reflecting means, or any combination thereof.

**Polarisation**

As discussed above OLCR can be extended through the use of polarized light. Accordingly, the optical ring circuit may further include a polarisation tuning device or polarisation maintaining fiber.

**Amplified spontaneous emission (ASE).**

In order to obtain the maximum achievable bandwidth it is preferred to address any amplified spontaneous emission in the system and observe relevant precautions. Accordingly, it is preferred that the optical ring circuit further includes means for reducing any amplified spontaneous emission (ASE).

Means for reducing amplified spontaneous emission is well known in the telecom industry, such means for example being the implementation in the optical ring circuit of a band pass filter, which tunes as the pulse tunes.

ASE and lasing is bidirectional, whereas the optical ring circuit is unidirectional. Thus, in some embodiments it is advantageous to include an isolator, such as a Faraday isolator, in order to reject the trajectories in the backwards direction.

**Pre-seeding**

In order to suppress start oscillations the optical ring circuit may be pre-seeded. Thus, in one embodiment the optical ring circuit is pre-seeded so that the amplification means has reached its saturated gain before starting scanning.

**Rounds**

The number of round-trips in each optical circuit, i.e. the number of repeats of steps c)-e) depends on the predetermined scanned wavelength range in view of the selected effective gain bandwidth of the active gain-medium(s) as well as the chirp rate of the chirped seed pulse. Hundreds or thousands of round-trips may be envisaged by the present invention.

The effective gain bandwidth of the laser source in total is preferably at least 15 nm, such as preferably at least 50 nm, such as preferably at least 100 nm, such as preferably at least 150 nm.

When using at least two optical ring circuits, a number of round-trips in the first ring are performed before transferring to the next ring for performing a number of round-trips in this ring. After the second ring, the output x may be used directly or input into a next optical ring circuit for another number of round-trips. Thus, the method and the system according to this invention may include at least three rings, such as at least four rings, wherein each ring is as defined above.

**Coupling**

The fraction y of the chirped pulse is re-injected into at least one optical ring circuit by any suitable means, such as through a fiber-coupling means or by use of free space coupling. For example a 2x2 fiber coupler with controlled loss would be useful, in particular if it is fusion-spliced into the optical ring circuit.

**Output**

In one embodiment it is preferred to include an amplifier after the optical ring circuit to amplify the total ring output.

In another embodiment the amplifier is incorporated to amplify only the fraction of the pulse to enter the ring for another round.

**Applications**

The substantially continuously swept frequency laser source may be applied in a variety of applications wherein a scanning frequency source is normally applied, such as mentioned above. In particular the laser source is useful is FDM transmission as well as in OLCR, and more particular in OCT wherein the high spatial axial resolution may be obtained due to the continuously scanned frequency of the laser source.

Thus, the laser source may be used in an apparatus used for so-called optical biopsies, wherein a segment of tissue, such as the skin, mucosa or any other solid tissue is examined by OCT to diagnose any cellular abnormalities, such as cancer or cancer in situ. Furthermore, any malignant growth may be detected by the present apparatus. Also, the present apparatus has improved the use of OCT in ophthalmic application due to the increased penetration depth, such as in corneal topography measurements and as an aid in ophthalmic surgery, for example for focusing on the posterior intraocular lens capsule for use in cataract surgery.

The present invention may also be applied in conventional OLCR applications, such as detection or imaging of inhomogeneities in optical waveguides or devices, i.e. wherein the sample is an optical waveguide or an integrated optical device.

Accordingly, the invention further relates to an apparatus for optical coherence reflectometry comprising

- a frequency scanning laser source as defined above for providing a light signal

- splitting means for dividing said light signal into a first light field and a second light field,

- means for directing the first light field to a sample, and means for directing a first reflected light field from the sample, to a combining means,

- means for directing the second light field to a reference path comprising a reflecting means, and means for directing a second reflected light field from the reference path to the combining means,

- combining means for receiving said first reflected light field and said second reflected light field to generate a combined light signal, and

- at least one detecting means for detecting the combined light signal and outputting detection signals.

The wavelength scanning laser source or frequency scanning laser source as described above including any of the variations discussed above provides the light signal for use in the apparatus.

In general the OLCR system or apparatus according to the invention may be constructed as either with an unbalanced detection system or a balanced detection system. The terms unbalanced and balanced are used in the normal meaning, ie. an unbalanced detection system refers to a system having one detecting means, whereas a balanced detection system refers to a system having two detecting means, wherein each detector receives signals from the sample arm as well as from the reference arm. In a balanced detection system the signals from the two detectors are subtracted from each other in order to obtain the result.

Also a double balanced detection system may be used in the apparatus according to the invention, a double balanced detection system referring to a system comprising four detecting means.

The signal in the OLCR system is obtained through a narrow line width light source where the frequency is scanned, and the resulting signal current is Fourier-transformed to obtain the desired information. If the optical frequency is scanned linearly and the source is assumed to only exhibit phase noise, the field from the source can be written as

$$E_{source}(t') = E_0 \exp[j(\omega(t')t' + \varphi_{t'})] \\ = E_0 \exp[j(\omega_0 t' + \pi\gamma t'^2 + \varphi_{t'})], \qquad (1)$$

where $\omega(t)$ is the angular frequency as a function of time, $\omega_0$ the initial angular seed pulse frequency, $\gamma$ the frequency scan speed, $E_0$ is the amplitude and $\varphi_t$ is the random fluctuation phase at time $t'$. The reference field and the field from the sample arm originate from the same source and can be written as:

$$E_{ref}(t) = E_r \exp[j(\omega_0 t + \pi\gamma t^2 + \varphi_t)] \qquad (2)$$

$$E_{sam}(t) = \int_{-\infty}^{\infty} \sqrt{r(\tau_0)} E_s \exp[j(\omega_0(t+\tau_0) + \pi\gamma(t+\tau_0)^2 + \varphi_{t+\tau_0})] d\tau_0, \qquad (3)$$

where $\tau_0$ is the time delay due to difference in optical path length between the sample and reference arm, $E_r$ and $E_s$ the respective amplitudes and $r(\tau_0)$ is a function describing the intensity reflectivity profile of the sample arm. This reflectivity profile includes the reflectivity profile of the sample and any undesired reflections in the sample arm e.g. from lenses, fiber ends, etc. Adapting the calculation of the spectrum of the received photocurrent given by S. Venkatesh and W. Sorin ("Phase Noise Considerations in Coherent Optical FMCW Reflectometry", J. of Lightw. Tech., VOL 11, No. 10, 1993) to a balanced detection system the single sided spectrum of the signal current is found to be

$$\frac{S(f)}{\alpha^2 E_r^2 E_s^2} = 2\exp\left[-\frac{|f|}{\tau_c \gamma}\right]\delta(f - f_b) \\ + \frac{4\tau_c}{1 + (2\pi|\tau_0|(f - f_b))^2}\left(1 - \exp\left[-\frac{\tau_0}{\tau_c}\right]\left(\cos(2\pi|\tau_0|(f - f_b)) + \frac{\sin(2\pi|\tau_0|(f - f_b))}{2\pi\tau_c(f - f_b)}\right)\right)$$

(4)

where $f_b=\gamma\tau_0$ is the beat frequency due to path length difference between the reference and sample fields, $\tau_c=1/2\pi\Delta\gamma$ is the coherence time of the light source and $\Delta\gamma$ is the full width half max (FWHM) of the line width of each pulse in the pulse train.

The first term of Eq.(4) is the signal due to the reflection in the sample arm, and the second term is a broadband noise contribution due to the phase noise of the light source. Inspecting Eq.(4) it is clear that since there is no mixing terms of the sample field with itself the current resulting from multiple reflections in the sample will be a superposition of the current resulting from each reflection had it been alone. Thus, the single sided spectrum of the signal current is found to be

$$\frac{S(f)}{\alpha^2 E_r^2 E_s^2} = 2\exp\left[-\left|f\right|\Big/\tau_c\gamma\right] r\left(f\Big/\gamma\right) + \int_{-\infty}^{\infty} \frac{4\tau_c r(\tau_0)}{1+\left(2\pi\left|\tau_0\right|(f-f_b)\right)^2}\left(1-\exp\left[-\tau_0\Big/\tau_c\right]\left(\cos\left(2\pi\left|\tau_0\right|(f-f_b)\right)+\frac{\sin\left(2\pi\left|\tau_0\right|(f-f_b)\right)}{2\pi\tau_c(f-f_b)}\right)\right)d\tau_0. \quad (5)$$

Any noise of the apparatus or system is preferably reduced as described in WO 02/21074 and WO 02/37075.

### Splitting means

The general principle of coherent optical reflectometry is that distance travelled by the light in the sample arm is correlated to the distance travelled by the light in the reference arm.

The light is emitted from a light source as discussed above and divided into a first light field and a second light field by a splitting means. The splitting means may be any means suitable for splitting a light signal into two light fields. The splitting means may be selected from any suitable splitting means, such as a bulk optic splitting means, a fibre optic splitting means, a holographic optical element or a diffractive optical element.

In one embodiment the apparatus according to the invention comprises a splitting means capable of dividing the light signal into the sample arm and the reference arm with a splitting ratio of the splitting means being substantially 50%/50%.

However the splitting ratio may be different from 50%/50%, for example as described in the two above defined WO publications.

**Sample arm – first light field route**

The apparatus according to the invention comprises means for directing the first light field to the sample. In a preferred embodiment at least a part of the means for directing the first light field to the sample comprises an optical fibre, so that the means in total comprises an optical fibre and an optical system. An optical system may be included for focusing the first light field to the sample, the optical system for example being one or more lenses.

The term light field as used herein means light field as normally used for the light in optical fibres, but does also include a light beam as normally used in bulk systems and in the optical system.

The sample is scanned by means known in the art, such as galvanometer scanners, polygon mirrors, resonant scanners, a scanning head.

**Reference arm - second light route**

The apparatus according to the invention also comprises means for directing the second light field to the combining means. In a preferred embodiment a device is included so that the optical path length of the second light route may be altered. In a preferred embodiment hereof at least a part of the directing means is comprised of an optical fiber and an optical fiber stretcher. In another preferred embodiment the device is a reflecting means such as a mirror setup. In this embodiment at least a part of the means for directing the second light field to the reflecting means comprises an optical fibre, so that the directing means in total comprises an optical fibre and an optical system. The optical system may be used for directing the second light field to the reflecting means, such as any kind of lenses, gratings etc. known to the person skilled in the art.

In a preferred embodiment the reflected second light field does not pass any splitting means for dividing the light signal when travelling back towards the combining means through the delivery fiber. It is an advantage to maintain as much as possible of the second light field on the route to the combining means. This may be accomplished by directing the second light field from the splitting means to the combining means in an optical fiber and if it is desired to alter the optical path length of the second light route to modulate the properties of the fiber. This may be done through a fiber stretcher to modulate the physical length of the fiber or by e.g. applying heat to alter the refractive index of the fiber. If a reflecting means is applied to alter the optical path length the light power may substantially be preserved by inserting a circulator to receive the second light field from the reflection means to direct the second light field directly to the combining means.

In a preferred embodiment a circulator is inserted to receive the second light field whereby substantially all light energy reflected from the reflecting means is directed as the second light field to the combining means.

The reflecting means may be any means suitable for reflecting the light in the reference arm. The reflecting means may be a mirror or another structure having reflective properties.

**Combining means**

The combining means is any suitable means capable of receiving two light fields and combining the light fields into at least one light signal. In a preferred embodiment the combining means is a coupler.

In an unbalanced detection system the combining means may be identical to the detecting means.

**Detecting means**

The system comprises conventional detecting means. The detecting means is essentially a photodetector chosen accordingly to match the source wavelength, a combination of photodetectors arranged to make up a balanced scheme, or a combination of photodetectors arranged to make up a double-balanced scheme.

Furthermore, the detecting means may be a linear array of photodetectors without or combined with a dispersive element arranged so that the array provides depth and spectral information. The detecting means may also be a linear charge-coupled device (CCD) array without or combined with a dispersive element arranged so that the array provides depth and spectral information.

Finally, the detecting means may be a two-dimensional array of photodetectors without or combined with a dispersive element arranged so that the array provides depth and spectral information. The detecting means may also be a two-dimensional CCD array without or combined with a dispersive element arranged so that the array provides depth and spectral information.

For example, the dispersive element may be a diffraction grating (reflection or transmission), a prism or a combination of prisms.

**Processing/displaying**

The result obtained may be further processed to obtain relevant information based on the detection signal relating to the distance/coherence. In one embodiment the detection signal is sent to a computer for analysis. Depending on the object scanned, the computer may provide an image relating to for example the tissue scanned.

In relation to detection of inhomogeneities in for example optical waveguides, the computer may provide information relating to the distance to the inhomogeneity and for example also an image of the inhomogeneity.

The result may be sent from the computer to a display and/or a printer and/or stored in a storage means.

**Penetration depth**

The parameters that govern coherent optical FMCW reflectometry performance are longitudinal and transverse resolution, dynamic range, measurement speed, and the centre wavelength of the light source.

The depth to which an illumination field of light penetrates within turbid media, such as biological tissue or the like, is determined by the amount of scattering and absorption present in the media.

In tissue scattering diminishes rapidly with increasing wavelength throughout the visible and infrared wavelength regions. Absorption in tissue is dominated by resonant absorption features, and no simple scaling can be assumed. For near-infrared light (~0.8 μm), where absorption is relatively weak, scattering is the dominant mechanism of attenuation. At longer wavelengths, such as 1.3 μm, 1.55 μm or 1.9 μm, scattering is minimal, and water absorption becomes increasingly important.

The transversal resolution is essentially given by the well-known diffraction limit, i.e. the minimum focal spot, which is the resolving power. The diffraction limit is determined by the wavelength, the effective aperture of the beam and the focal length of the lens as known from the art.

**Transverse scanning**

The light path preferably includes a transverse scanning mechanism for scanning the probe beam within the sample, for example an actuator for moving the apparatus in a direction substantially perpendicular to the sample. Such a scanning mechanism can have a micro-machined scanning mirror. Scanning allows the apparatus to create images.

It is of course understood that although it is preferred to scan the sample apparatus in relation to the sample, the sample may also be scanned with respect to a stationary sample probe or a combination of these.

The present invention further relates to a method for providing a result image of a sample comprising

- establishing a frequency scanning laser source as defined above for providing a light signal,

- splitting said light signal into a first light field and a second light field,

- directing the first light field to a sample, and the second light field to a reference path,

- receiving the first reflected light field from the sample, and the second reflected light field from the reference path,

- combining said first reflected light field and said second reflected light field to generate a combined light signal,

- detecting the combined light signal obtaining detection signals, and

- processing the detection signals obtaining the result image of the sample.

The method includes any of the features described above in relation to the laser source as well as the optical coherence reflectometry apparatus.

In the present context the term “result of the sample” may refer in coherent optical reflectometry to the image of the sample obtained.

## Examples

### Example 1

System including a chirped source with or without internal chirp

The system shown in **Fig. 1** is an unbalanced interferometer for use with a chirped source. The scanning frequency source exhibits a linear chirp as a function of time $\omega(t)$

$$w(t) = w_0 + a\,t, \qquad \textbf{(1)}$$

where $\omega_0$ is the source frequency and α the chirp rate with $[\alpha]=\text{Hz s}^{-1}$. The light reflected from the reference mirror to the detector is

$$E_R(t) = E_R \exp\{-j\omega(t)t\} = E_R \exp\left\{-j\left(\omega_0 + \frac{2\alpha L}{c}\right)t\right\}, \qquad \textbf{(2)}$$

where $c$ is the speed of light and $2L$ the reference path length. Similarly, the light reflected from a single discontinuity at depth $\delta L$ may be written as

$$E_s(t) = E_s \exp\{-j\omega(t)t\} = E_s \exp\left\{-j\left(\omega_0 + \frac{2\alpha(L+\delta L)}{c}\right)t\right\}. \qquad (3)$$

The two fields mix at the detector and the AC part of the resulting current $i_D(t)$ is proportional with

$$i_D(t) \propto E_R E_S \cos\left(\frac{2\alpha\delta L}{c}t\right). \qquad (4)$$

From the power spectrum of the Fourier transform of the detector current $i_D(t)$ the reflection from the single discontinuity is determined as a delta-function located at (2 α $\delta L$ / $c$). Hence, depth information is converted into the (temporal) frequency domain.

Source requirements

To obtain the above-mentioned operation, it is imperative that the chirp is linear, i.e. exhibits a truly linear behavior as shown in **Fig. 2** by the solid line. If, on the other hand, the behavior outlined in **Fig. 2** by the dashed line were inserted into the interferometer, the effective chirp would be strongly reduced and therefore the spatial resolution would be poor. Note that the resolution essentially would equal that of the pulse separation.

The source emits a pulse train with 50 ns pulse width and the pulses are separated by 50 ns. Furthermore, in each pass of the ring resonator the pulse receives a 200 MHz frequency offset from the acousto-optic modulator.

This behaviour corresponds to the dashed curve in **Fig. 2**. Therefore, the effective chirp is much less than expected with resulting poor spatial resolution.

In Fig. 3 is sketched a situation wherein the laser is pulsed with finite pulse separation, the frequency versus time will be modulated with a square-wave function. Hence, at times there is no light inserted into the interferometer.

The operation shown in **Fig. 3** may be obtained by meeting the following condition:

$$\frac{df}{dt}\tau_{round} = f_{a.o.m.}, \qquad \textbf{(5)}$$

where $df/dt$ is the chirp rate of the initial pulse, $\tau_{round}$ the roundtrip time for the ring resonator and $f_{a.o.m.}$ the frequency offset imposed by the acousto-optic modulator.

By using the above criterion, the chirp in the pulse to be injected may be found. From **(5)** the chirp rate $df/dt$ is found to $df/dt = 4 \times 10^{15}$ Hz/s. From the relation $c = \lambda f$, where $\lambda$ is the wavelength, the following relation is deduced:

$$\begin{aligned} \frac{d\lambda}{dt} &= \frac{\lambda^2}{c}\frac{df}{dt} \\ &= \frac{(1050\ \mathrm{nm})^2}{3 \times 10^{8}\,\mathrm{m/s}} 4 \times 10^{15}\,\mathrm{Hz/s} \qquad \textbf{(6)} \\ &= 1.47 \times 10^{-5}\,\mathrm{m/s} = 7.35 \times 10^{-4}\,\mathrm{nm/50ns} \end{aligned}$$

The chirp found in **(6)** may be converted to Hz by using the relation $c = \lambda f$, to yield 200 MHz/50ns.

The off-times, see **Fig. 3**, are equivalent to so-called mode-hopping. This effect increases the noise floor in the temporal Fourier domain, and it may have an influence on the resolution of the system. However, mode-hopping will affect the heterodyne signal only if the phase of the detected signal changes between adjacent pulses in the output pulse train, which may not be the case. Our previous investigation showed that the phase remained unchanged even though mode hopping occurred.

**Example 2**

**Schematic presentation of the scanning laser source with one optical ring circuit**

Fig. 4 shows a schematic realization of scanning ring laser with one optical ring circuit.

A fraction (1-x) of the chirped seed pulse is fed to the ring laser through a first fiber-coupling means and a fraction x is coupled to the output. The (1-x) fraction propagates through a polarization controlling means and a wavelength shifting device: Each round-trip the pulse wavelength is shifted upwards or downwards, respectively. The fraction (1-x) of the chirped seed pulse enters the excited active fiber, where it is amplified each round trip by a single pass of the active fiber. The active fiber is pumped optically to its excited state by single-end pumping, and the direction of the pump is opposite that of the pulse being amplified. The amplified pulse exits the active fiber, and after passing a length of passive optical fiber, a fraction x of the amplified (and wavelength-shifted) pulse exits the ring laser by a fiber-coupling means. By adjusting the input chirped seed pulse temporal duration with respect to the round trip time and the fixed wavelength shift, the output of the ring laser will be a pulse train in which the wavelength effectively is scanned over a large bandwidth as determined by the gain medium characteristics of the active fiber. After the full scan another chirped seed pulse is inserted into the system thus yielding a repeatedly wavelength scanning output of the ring laser.

**Example 3**

**Schematic presentation of the scanning laser source with two optical ring circuits arranged in series**

Fig. 5 shows a schematic realization of another embodiment of the scanning ring laser of Fig. 4, namely a scanning ring laser with two optical ring circuits. When the end of the gain bandwidth of the gain medium in the first optical ring is reached, switching means is responsible for directing the last pulse to the next optical ring circuit. This pulse will now act as the chirped seed pulse for the second optical ring. Laser output 1 and 2 may be combined by using a 2x1 fiber coupler with one arm being longer than the other in order to temporally match the two laser outputs.

**Example 4**

**Schematic presentation of the scanning laser source with one optical ring circuit having n gain-media arranged in parallel**

Fig. 6 shows a schematic realization of another embodiment of the scanning ring laser of Fig. 4, namely a scanning ring laser with 1 - n gain media arranged in parallel in the optical ring circuit. When the end of the gain bandwidth of a single gain medium is reached, a switch is responsible for directing the subsequent pulses to the next gain medium.

**Claims**

1. A method for producing a substantially continuously swept frequency laser source output, said method comprising

a) providing a frequency chirped seed pulse having a chirp rate df/dt, said chirp rate df/dt being different from zero, and providing

- at least one optical ring circuit, said at least one optical ring circuit comprising a frequency shifting device, at least two active gain media arranged in parallel, and optionally an optical delay line, or

- at least two separate optical ring circuits arranged in series, said at least two optical ring circuits comprising a frequency shifting device, at least one active gain medium, and optionally an optical delay line,

b) injecting at least a fraction of said chirped seed pulse to at least one optical ring circuit,

c) shifting frequency of said fraction of said chirped pulse in the optical ring circuit, obtaining a frequency shifted chirped pulse,

d) amplifying the chirped pulse in the optical ring circuit, obtaining an amplified pulse,

e) extracting a fraction x of the amplified frequency shifted chirped pulse as laser output, and reinjecting a fraction y of the amplified frequency shifted chirped pulse into at least one optical ring circuit,

f) optionally repeating the steps c) to e) at least once, whereby the fraction y of the amplified frequency shifted chirped pulse is regulated in step d),

g) obtaining a substantially continuously swept frequency laser source output with substantially smooth frequency sweep, and

h) optionally repeating the steps a) to g) at least once obtaining a series of substantially continuously swept frequency laser source output each with substantially smooth frequency sweep.

2. A method for producing a substantially continuously swept frequency laser source output, said method comprising

a) providing a frequency chirped seed pulse having a chirp rate df/dt, said chirp rate df/dt being different from zero, and providing at least one optical ring circuit, said at least one optical ring circuit comprising a frequency shifting device, at least one active fibre, and optionally an optical delay line, wherein the at least one active fibre is pumped optically by at least two laser diodes, one of said two laser diodes having a first wavelength and the other of said two laser diodes having a second wavelength,

b) injecting at least a fraction of said chirped seed pulse to at least one optical ring circuit,

c) shifting frequency of said fraction of said chirped pulse in the optical ring circuit, obtaining a frequency shifted chirped pulse,

d) amplifying the chirped pulse in the optical ring circuit, obtaining an amplified pulse,

e) extracting a fraction x of the amplified frequency shifted chirped pulse as laser output, and reinjecting a fraction y of the amplified frequency shifted chirped pulse into at least one optical ring circuit,

f) optionally repeating the steps c) to e) at least once, whereby the fraction y of the amplified frequency shifted chirped pulse is regulated in step d),

g) obtaining a substantially continuously swept frequency laser source output with substantially smooth frequency sweep, and

h) optionally repeating the steps a) to g) at least once obtaining a series of substantially continuously swept frequency laser source output each with substantially smooth frequency sweep.

3. The method according to claim 1 or 2, wherein the chirp rate df/dt equals the frequency shift per round trip time in the optical ring.

4. The method according to claim 3, wherein the chirp rate df/dt is in the range of from 25 MHz – 10 GHz per round trip time in the optical ring.

5. The method according to any of the preceding claims, wherein the chirp of the frequency chirp pulse in step a) is a linear chirp.

6. The method according to any of the preceding claims, wherein the frequency chirped seed pulse is provided from a tunable (grating, thermal) laser diode source, diode pumped solid state laser source, and frequency swept ASE source.

7. The method according to any of the preceding claims, wherein the total length of the optical ring circuit is matched to or longer than the corresponding pulse width.

8. The method according to claim 7, wherein the pulse width is in the range of from 25-500 ns.

9. The method according to any of the preceding claims, wherein the active gain medium is selected from a discrete crystal or multiple crystals of gain medium, or an active fiber, or multiple different active fibers having compositionally tuned gain bandwidths so as to increase the effective bandwidth.

10. The method according to any of the preceding claims, wherein the active gain medium is an active fiber.

11. The method according to claim 10, wherein the active fiber is a rare earth doped fiber, such as a fiber selected from a Neodymium doped fiber, a Ytterbium

doped fiber, an Erbium doped fiber, or a Thulium doped fiber or combinations thereof.

12. The method according to claim 11, wherein the active fiber is a photonic crystal fiber.

13. The method according to any one of claims 10-12, wherein the active fiber has a double clad structure.

14. The method according to any of the preceding claims, wherein at least one optical ring circuit comprises at least two different gain media arranged in parallel in the optical ring circuit.

15. The method according to claim 14, wherein a switching means is arranged in the optical ring circuit capable of switching from one gain medium to another gain medium.

16. The method according to any of the preceding claims, wherein at least two separate optical ring circuits are arranged in series.

17. The method according to claim 16, wherein the gain medium of each separate optical ring circuit is identical.

18. The method according to any of the preceding claims, wherein the fraction y of said chirped pulse is reinjected into at least one optical ring circuit through a fiber-coupling means or by use of free space coupling.

19. The method according to claim 16, wherein the gain medium of one optical ring circuit is different from the gain medium of another ring circuit.

20. The method according to any of the preceding claims, wherein the fraction y of the amplified frequency shifted chirped pulse is regulated by amplification in step d) to compensate for the extracted fraction x.

21. The method according to any of the preceding claims, wherein the fraction y of the amplified frequency shifted chirped pulse is regulated by amplification in step d) to compensate for optical losses in the optical ring circuit.

22. The method according to any of the preceding claims, wherein the frequency shifting device is selected from an acousto-optic device or an electro-optic device.

23. The method according to any of the preceding claims, wherein the frequency shifting device is capable of providing a frequency offset $f_{offset}$ in the range of from 25 MHz – 10 GHz.

24. The method according to any of the preceding claims, wherein the optical delay line is selected from a passive fiber, free space, reflecting means, or any combination thereof.

25. The method according to any of the preceding claims, wherein the optical ring circuit further includes a polarisation tuning device or polarisation maintaining fiber.

26. The method according to any of the preceding claims, wherein the optical ring circuit further includes means for reducing any amplified spontaneous emission (ASE).

27. The method according to any of the preceding claims, wherein the means for reducing amplified spontaneous emission is a band pass filter, which tunes as the pulse tunes.

28. The method according to any of the preceding claims, wherein the steps c)-e) are repeated for a number of times, depending on the predetermined scanned wavelength range of the gain bandwidth of the optical amplification means.

29. The method according to claim 28, wherein the gain bandwidth is at least 15 nm.

30. The method according to any of the preceding claims, wherein the active fiber is pumped optically by at least one laser diode, using at least one frequency resonantly absorbed in the fiber.

31. The method according to claim 28, wherein the active fiber is pumped optically by two laser diodes, one of said two laser diodes having a first wavelength and the other of said two laser diodes having a second wavelength.

32. The method according to claim 28, wherein the first wavelength is different from the second wavelength.

33. The method according to claim 28, wherein the first wavelength and the second wavelength are at least substantial identical.

34. The method according to any of the preceding claims, wherein the active fiber is pumped optically in an end pumped configuration, or in a v-groove configuration.

35. The method according to claim 34, wherein the active fiber is a double-clad fiber.

36. The method according to any of the preceding claims, wherein the core of the active fiber is pumped directly.

37. The method according to any of the preceding claims, wherein the wavelength range of the chirped pulse in step a) is selected within the optical gain band width of the active fiber.

38. A substantially continuously frequency scanning laser source comprising

a) a light source capable of providing a frequency chirped seed pulse having a chirp rate df/dt, said chirp rate df/dt being different from zero,

b) coupling means for injecting at least a fraction of said chirped seed pulse into at least one optical ring circuit,

c) at least one optical ring circuit, said at least one optical ring circuit comprising a frequency shifting device, at least two active gain media arranged in parallel, and optionally an optical delay line, or

at least two separate optical ring circuits arranged in series, said at least two optical ring circuits comprising a frequency shifting device, at least one active gain medium, and optionally an optical delay line,

d) out-put coupling means for extracting a fraction x of the frequency shifted chirped pulse as laser output.

39. A substantially continuously frequency scanning laser source comprising

a) a light source capable of providing a frequency chirped seed pulse having a chirp rate df/dt, said chirp rate df/dt being different from zero,

b) coupling means for injecting at least a fraction of said chirped seed pulse into at least one optical ring circuit,

c) at least one optical ring circuit, said at least one optical ring circuit comprising a frequency shifting device, at least one active fibre, and optionally an optical delay line, at least two laser diodes, one of said two laser diodes having a first wavelength and the other of said two laser diodes having a second wavelength, said laser diodes being arranged so that the at least one active fibre is pumped optically by at least two laser diodes,

d) out-put coupling means for extracting a fraction x of the frequency shifted chirped pulse as laser output.

40. The laser source according to claim 38 or 39, wherein the chirp rate df/dt equals the frequency shift per round trip time in the optical ring.

41. The laser source according to claim 40, wherein the chirp rate df/dt is in the range of from 25 MHz – 10 GHz per round trip time in the optical ring.

42. The laser source according to any one of claims 38-41, wherein the chirp of the frequency chirp pulse in step a) is a linear chirp.

43. The laser source according to any one of claims 38-42, wherein the frequency chirped seed pulse is provided from a tunable (grating, thermal) laser diode source, diode pumped solid state laser source, and frequency swept ASE source.

44. The laser source according to any one of claims 38-43, wherein the total length of the optical ring circuit is matched to or longer than the corresponding pulse width.

45. The laser source according to claim 44, wherein the pulse width is in the range of from 25-500 ns.

46. The laser source according to any one of claims 38-45, wherein the active gain medium is selected from a discrete crystal or multiple crystals of gain medium, or an active fiber, or multiple different active fibers having compositionally tuned gain bandwidths so as to increase the effective bandwidth.

47. The laser source according to any one of claims 38-46, wherein the active gain medium is an active fiber.

48. The laser source according to claim 47, wherein the active fiber is a rare earth doped fiber, such as a fiber selected from a Neodymium doped fiber, a Ytterbium doped fiber, an Erbium doped fiber, or a Thulium doped fiber or combinations thereof.

49. The laser source according to claim 47, wherein the active fiber is a photonic crystal fiber.

50. The laser source according to any one of claims 47-49, wherein the active fiber has a double clad structure.

51. The laser source according to any one of claims 38-50, wherein at least one optical ring circuit comprises at least two different gain media arranged in parallel in the optical ring circuit.

52. The laser source according to claim 51, wherein a switching means is arranged in the optical ring circuit capable of switching from one gain medium to another gain medium.

53. The laser source according to any one of claims 38-52, wherein at least two separate optical ring circuits are arranged in series.

54. The laser source according to claim 53, wherein the gain medium of each separate optical ring circuit is identical.

55. The laser source according to any one of claims 38-54, wherein the fraction y of said chirped pulse is reinjected into at least one optical ring circuit through a fiber-coupling means or by use of free space coupling.

56. The laser source according to claim 55, wherein the gain medium of one optical ring circuit is different from the gain medium of another ring circuit.

57. The laser source according to any one of claims 38-56, wherein the fraction y of the amplified frequency shifted chirped pulse is regulated by amplification in step d) to compensate for the extracted fraction x.

58. The laser source according to any one of claims 38-57, wherein the fraction y of the amplified frequency shifted chirped pulse is regulated by amplification in step d) to compensate for optical losses in the optical ring circuit.

59. The laser source according to any one of claims 38-58, wherein the frequency shifting device is selected from an acousto-optic device or an electro-optic device.

60. The laser source according to any one of claims 38-59, wherein the frequency shifting device is capable of providing a frequency offset $f_{offset}$ in the range of from 25 MHz – 10 GHz.

61. The laser source according to any one of claims 38-60, wherein the optical delay line is selected from a passive fiber, free space, reflecting means, or any combination thereof.

62. The laser source according to any one of claims 38-61, wherein the optical ring circuit further includes a polarisation tuning device or polarisation maintaining fiber.

63. The laser source according to any one of claims 38-62, wherein the optical ring circuit further includes means for reducing any amplified spontaneous emission (ASE).

64. The laser source according to any one of claims 38-63, wherein the means for reducing amplified spontaneous emission is a band pass filter, which tunes as the pulse tunes.

65. The laser source according to any one of claims 38-64, wherein the steps c)-e) are repeated for a number of times, depending on the predetermined scanned wavelength range of the gain bandwidth of the optical amplification means.

66. The laser source according to claim 65, wherein the gain bandwidth is at least 15 nm.

67. The laser source according to any one of claims 38-66, wherein the active fiber is pumped optically by at least one laser diode, using at least one frequency resonantly absorbed in the fiber.

68. The laser source according to claim 67, wherein the active fiber is pumped optically by two laser diodes, one of said two laser diodes having a first wavelength and the other of said two laser diodes having a second wavelength.

69. The laser source according to claim 67, wherein the first wavelength is different from the second wavelength.

70. The laser source according to claim 67, wherein the first wavelength and the second wavelength are at least substantial identical.

71. The laser source according to any one of claims 38-70, wherein the active fiber is pumped optically in an end pumped configuration, or in a v-groove configuration.

72. The laser source according to claim 71, wherein the active fiber is a double-clad fiber.

73. The laser source according to any one of claims 38-72, wherein the core of the active fiber is pumped directly.

74. The laser source according to any one of claims 38-73, wherein the wavelength range of the chirped pulse in step a) is selected within the optical gain band width of the active fiber.

75. An apparatus for optical coherence reflectometry comprising

- a frequency scanning laser source as defined in any one of claims 38-74 for providing a light signal

- splitting means for dividing said light signal into a first light field and a second light field,

- means for directing the first light field to a sample, and means for directing a first reflected light field from the sample, to a combining means,

- means for directing the second light field to a reference path comprising a reflecting means, and means for directing a second reflected light field from the reference path to the combining means,

- combining means for receiving said first reflected light field and said second reflected light field to generate a combined light signal, and

- at least one detecting means for detecting the combined light signal and outputting detection signals.

76. A method for providing a result image of a sample comprising

- establishing a frequency scanning laser source as defined in any one of claims 38-74 for providing a light signal,

- splitting said light signal into a first light field and a second light field,

- directing the first light field to a sample, and the second light field to a reference path,

- receiving the first reflected light field from the sample, and the second reflected light field from the reference path,

- combining said first reflected light field and said second reflected light field to generate a combined light signal,

- detecting the combined light signal obtaining detection signals, and

- processing the detection signals obtaining the result image of the sample.

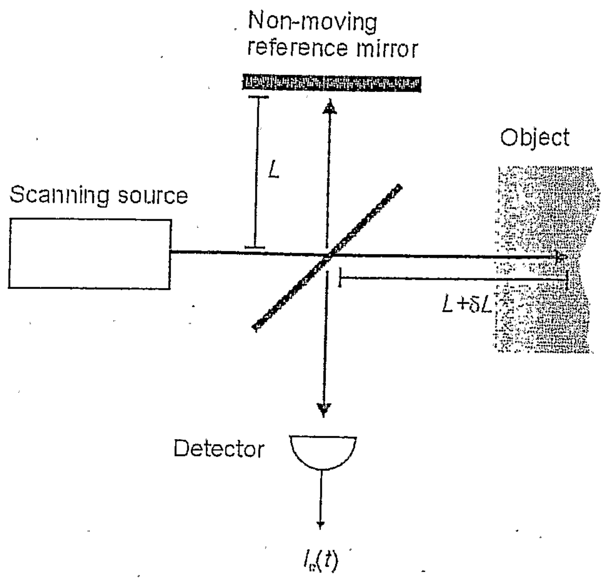
Non-moving
reference mirror
L
Object
Scanning source
L+δL
Detector
$I_c(t)$

Fig. 1

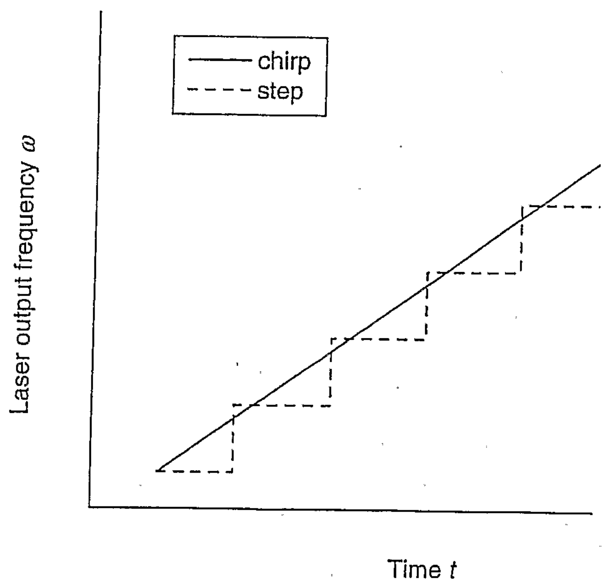
chirp
step
Laser output frequency ω
Time t

Fig. 2

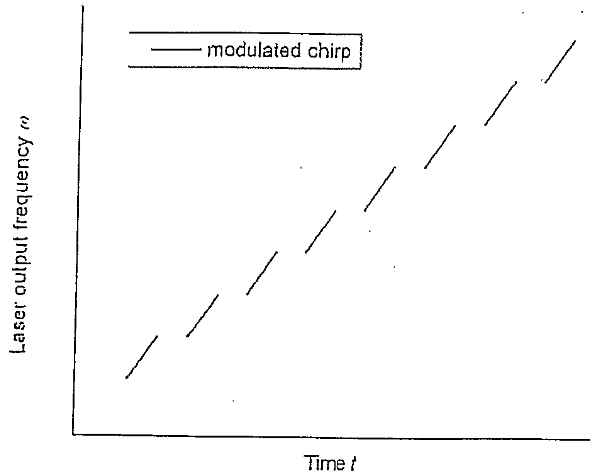
modulated chirp
Laser output frequency ω
Time t

Fig. 3

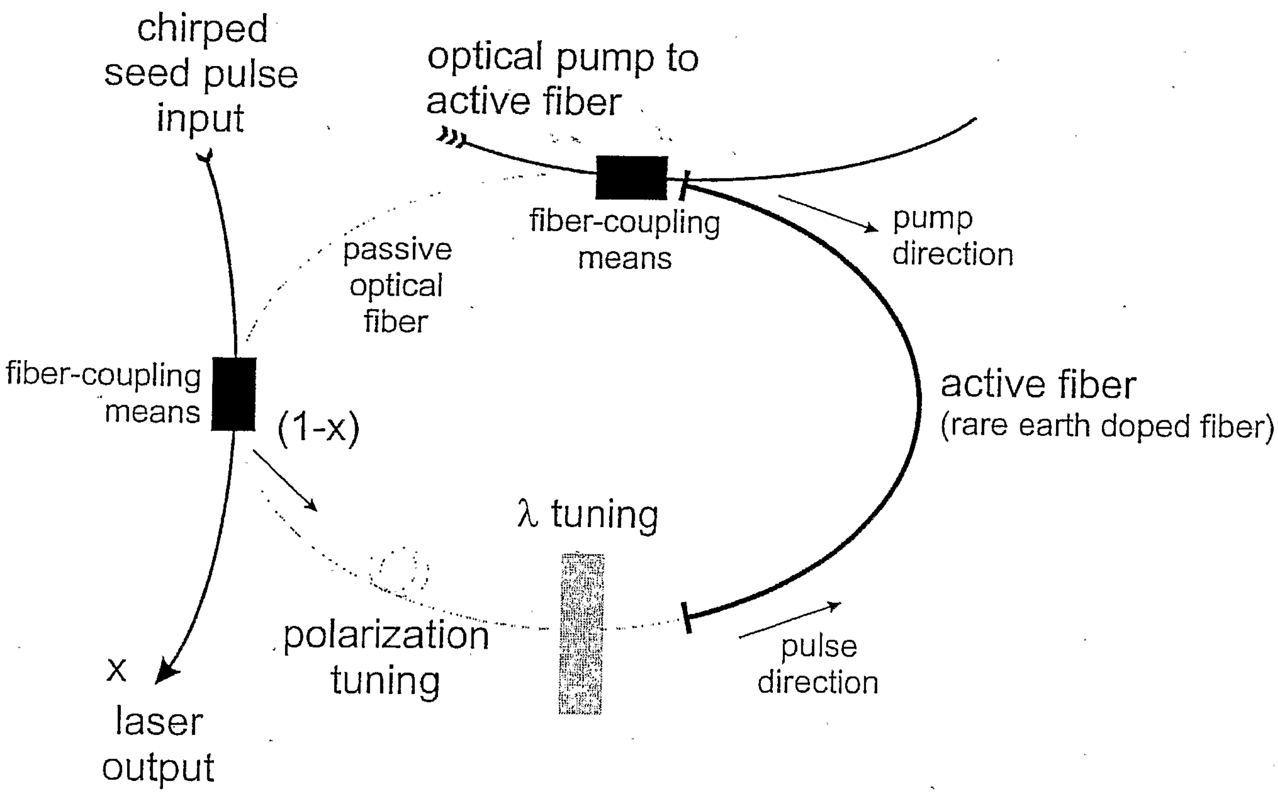
chirped seed pulse input
optical pump to active fiber
fiber-coupling means
pump direction
passive optical fiber
fiber-coupling means
(1-x)
active fiber
(rare earth doped fiber)
λ tuning
polarization tuning
pulse direction
x
laser output

Fig. 4

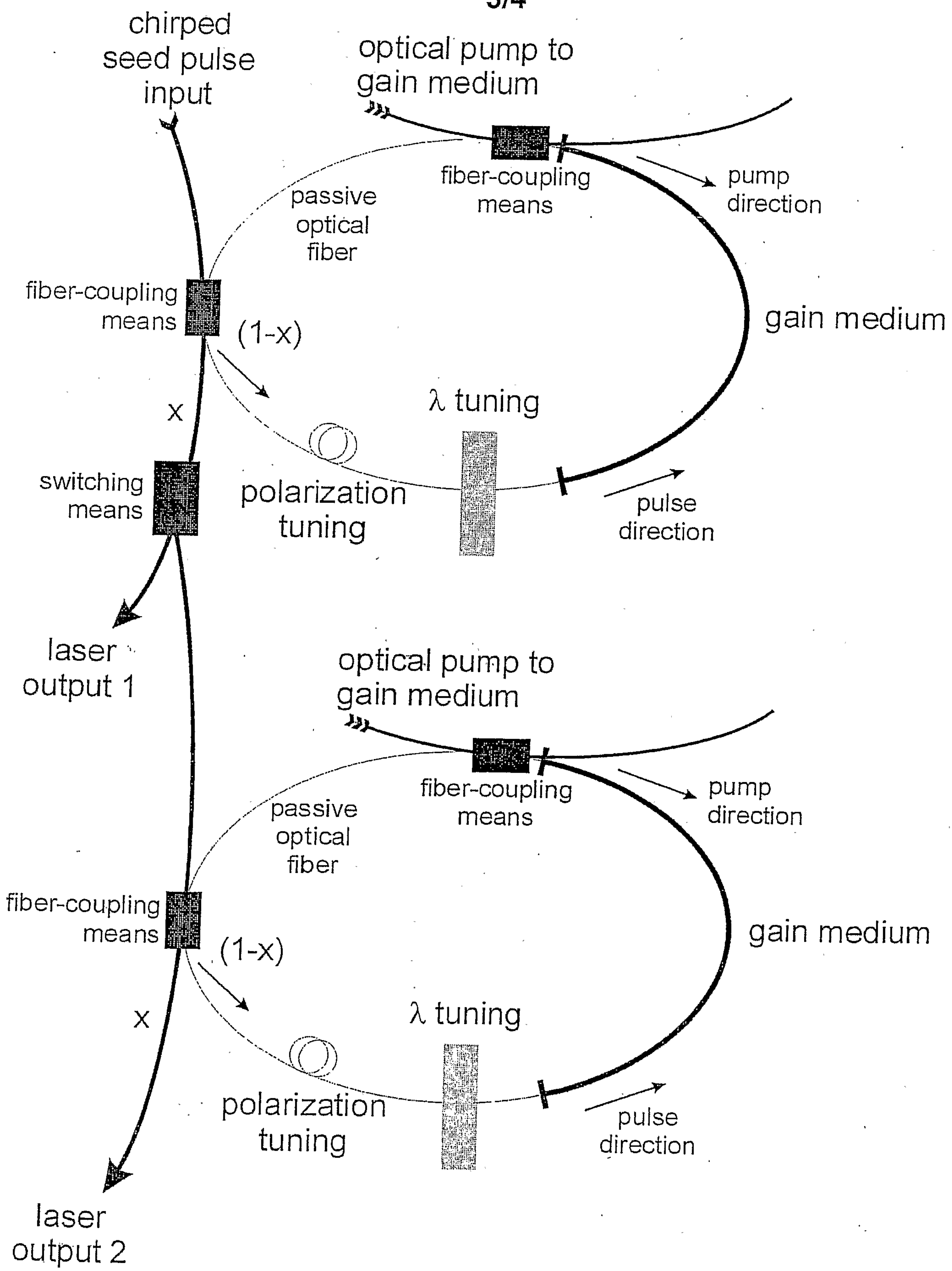
chirped
seed pulse
input
optical pump to
gain medium
fiber-coupling
means
pump
direction
passive
optical
fiber
fiber-coupling
means
(1-x)
gain medium
x
λ tuning
switching
means
polarization
tuning
pulse
direction
laser
output 1
optical pump to
gain medium
fiber-coupling
means
pump
direction
passive
optical
fiber
fiber-coupling
means
(1-x)
gain medium
x
λ tuning
polarization
tuning
pulse
direction
laser
output 2

Fig. 5

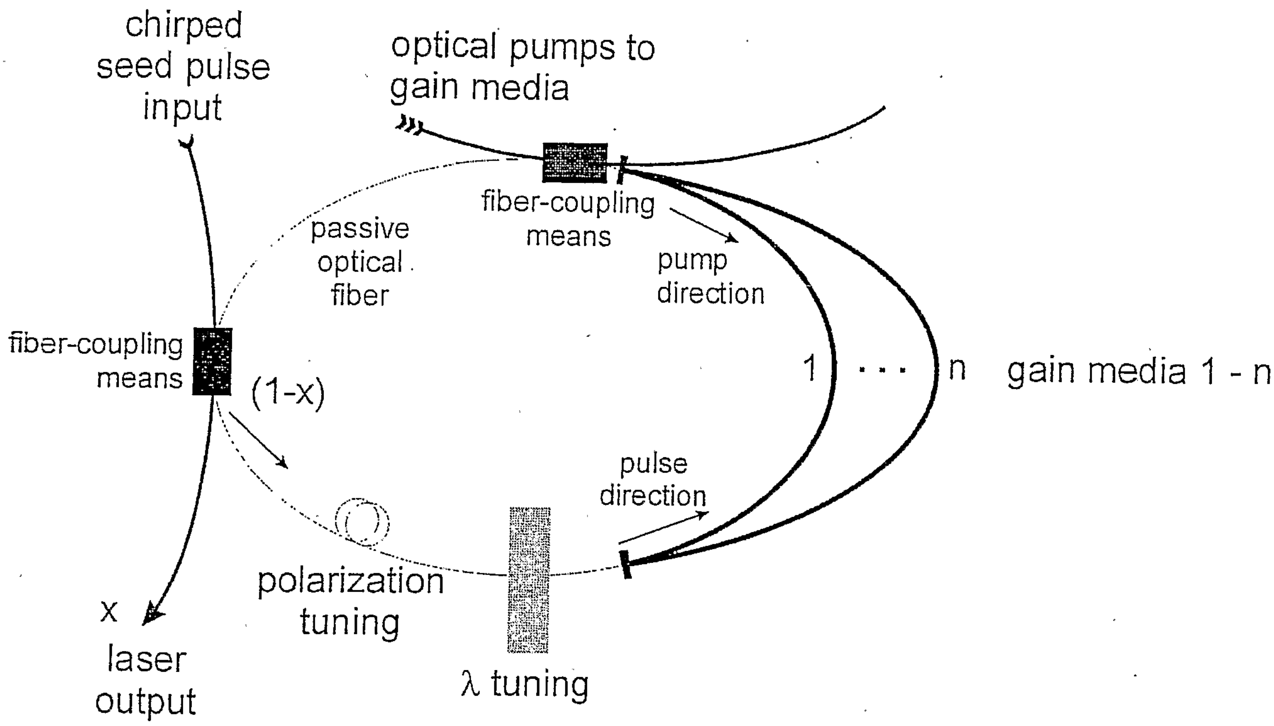
chirped
seed pulse
input
optical pumps to
gain media
fiber-coupling
means
passive
optical
fiber
pump
direction
fiber-coupling
means
(1-x)
1 · · · n
gain media 1 - n
pulse
direction
polarization
tuning
x
laser
output
λ tuning

Fig. 6

# INTERNATIONAL SEARCH REPORT

International Application No
PCT/DK2004/000570

**A. CLASSIFICATION OF SUBJECT MATTER**
IPC 7 H01S3/067 G02F2/02 A61B5/00

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 7 H01S G02F A61B

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, INSPEC

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category ° | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| A | SHIMIZU K ET AL: "ABSOLUTE FREQUENCY SYNTHESIS OF PULSED COHERENT LIGHT WAVES THROUGHPHASE-MODULATION ACTIVE OPTICAL FEEDBACK" OPTICS LETTERS, OPTICAL SOCIETY OF AMERICA, WASHINGTON, US, vol. 21, no. 22, 15 November 1996 (1996-11-15), pages 1824-1826, XP000639724 ISSN: 0146-9592 page 1824, left-hand column, last paragraph - page 1825, left-hand column, paragraph 1; figure 1 page 1825, left-hand column, last paragraph - right-hand column, paragraph 1; figure 3 ----- | 1-76 |

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

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

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"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

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"&" document member of the same patent family

| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 20 December 2004 | 28/12/2004 |

| Name and mailing address of the ISA | Authorized officer |
|---|---|
| European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Tx. 31 651 epo nl, Fax: (+31–70) 340–3016 | Flierl, P |

Form PCT/ISA/210 (second sheet) (January 2004)

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

| Category ° | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
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| A | PRICE J H V ET AL: "A tunable, femtosecond pulse source operating in the range 1.06-1.33 microns based on an Yb doped holey fiber amplifier" CONFERENCE ON LASERS AND ELECTRO-OPTICS. (CLEO 2001). TECHNICAL DIGEST. POSTCONFERENCE EDITION. BALTIMORE, MD, MAY 6-11, 2001, TRENDS IN OPTICS AND PHOTONICS. (TOPS), US, WASHINGTON, WA : OSA, US, vol. VOL. 56, 6 May 2001 (2001-05-06), pages CPD1-1, XP002228538 ISBN: 1-55752-662-1 paragraph ‘0001! - paragraph ‘0002!; figure 1 | 1-76 |
| P,A | DE 103 02 785 A (MENLO SYSTEMS GMBH) 19 August 2004 (2004-08-19) abstract; figure 3 | 1-76 |
| A | HABERLAND U H P ET AL: "Chirp optical coherence tomography of layered scattering media" JOURNAL OF BIOMEDICAL OPTICS SPIE USA, vol. 3, no. 3, 1 July 1998 (1998-07-01), pages 259-266, XP2309768 ISSN: 1083-3668 cited in the application abstract; figure 1 | 1-76 |
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# INTERNATIONAL SEARCH REPORT

**Information on patent family members**

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PCT/DK2004/000570

| Patent document cited in search report | Publication date | Patent family member(s) | Publication date |
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| | | EP 1378034 A2 | 07-01-2004 |
| | | WO 02084821 A2 | 24-10-2002 |
| | | JP 2004527001 T | 02-09-2004 |
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