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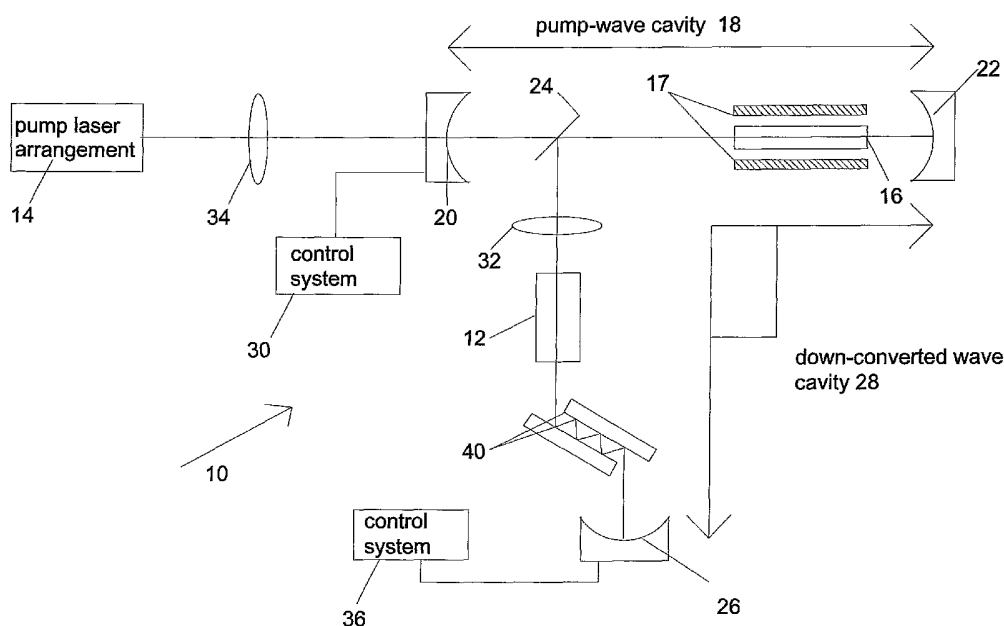
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(54) Title: FREQUENCY COMB GENERATOR



(57) Abstract: A frequency comb generator (10) comprising a non-linear material (16), such as a non-linear crystal, that produces two or more down-converted waves when optically stimulated using an optical pump (14). The generator (10) has two optical cavities (18, 28), the first (18) being a pump wave cavity in which radiation from the pump is resonant, the second being a down converted wave cavity (28) in which one or more of the down-converted waves is resonant. The non-linear material (16) is included in the pump cavity. Included in the down-converted cavity (28) is a phase modulator (12).



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FREQUENCY COMB GENERATOR

This invention relates to the field of optical frequency generators and specifically the generation of a large number of simultaneous optical frequencies that are separated by a regular interval. This is sometimes referred to as frequency comb generation.

In order to effectively exploit the substantial bandwidths and hence potential volume of data transfer associated with optical communications, wavelength division multiplexing (WDM) is widely used. There is a need in such an approach to be able to excite (i.e. to provide power for) a large number of optical channels, separated in optical frequency, such that different messages/information may be transmitted independently along the different channels and without experiencing interference between channels. In order to accomplish this, coherent or partially coherent radiation must be generated at different carrier frequencies corresponding to the different channels, and information must be impressed upon the radiation so generated. Typically different information is impressed on different channels. The radiation corresponding to the different channels is then propagated down, for example, an optical fibre, the information so transmitted being recovered from the different channels by separating the channels according to their carrier frequencies at the receiver. Such systems have been widely described, for example in "A review of WDM technology and applications" by G. E. Keiser in Optical Fiber Technology vol.5 pp.3-39 (1999) and "Wavelength domain optical networks" by G. R. Hill in Proceedings IEEE vol.78 (1) pp.121-132 (1990).

Various systems are currently available to generate the optical radiation that defines the channels. One such system is a frequency comb generator. This is a device

that generates radiation in such a way that the optical frequencies/channels are both numerous and equally spaced in frequency by a precisely controllable and adjustable amount. These devices are such that if one of the
5 frequencies in the comb is defined in terms of some appropriate optical frequency standard, then this also precisely determines the frequencies of all the other optical channels in the comb, and all these channels remain equally spaced in frequency.

10 Existing frequency comb generators based on a single primary source of coherent radiation incorporate a resonant optical cavity and phase modulator, see for example M. Kourogi et al "Wide span optical frequency comb generator for accurate optical frequency difference
15 measurement" in IEEE Journal Quantum Electronics vol.29 (10) pp.2693-2701 (1993). Radiation at the fundamental frequency f derived from a single coherent source, e.g. a semiconductor diode laser, is coupled into a resonant optical cavity. Within same cavity a phase modulator is
20 incorporated, driven by a radio frequency or microwave oscillator at frequency v , where v is an integer multiple of the cavity free spectral range frequency. The phase modulator acts so as to transfer energy from the fundamental frequency wave into two new sidebands at
25 frequencies $f \pm v$. As these new frequencies are also resonant within the optical cavity these sidebands are re-circulated through the phase modulator so producing secondary sidebands which in turn generate their own sidebands and so on.

30 The spectral extent of the generated comb in the system described by Kourogi et al is limited to around 5 THz, see for example M. Kourogi et al "Limit of optical-frequency comb generation due to material dispersion" in IEEE Journal Quantum Electronics vol.31 (12) pp.2120-2126

(1995). This limitation of the spectral extent is caused by a combination of features, such as the modulation index of the phase modulator, the finesse of the optical cavity, phase mismatch errors due to inexact setting of the phase modulator oscillation frequency and the cavity free spectral range and dispersion in the optics. By employing dispersion compensation techniques in optical resonators; such as dispersion compensation prisms, dispersion compensation multi-layer coatings or dispersion compensation optical fibers, the spectral extent of the generated comb can be increased. For example, a 50 THz wide comb was reported by L. R Brothers and N. C. Wong "Dispersion compensation for terahertz optical frequency comb generation" in Optics Letters vol.22 (13) pp1015-1017 (1997) and K. Imai et al reported a comb of 12 THz in "12-THz frequency difference measurements and noise analysis of an optical frequency comb in optical fibers" in the IEEE Journal Quantum Electronics vol.35 (4) pp.559-564 (1999). In the context of for example wavelength division multiplexing (WDM) applications, a disadvantage of the aforesaid technique is that the optical power in the generated sidebands decays exponentially in frequency space. It is desirable in such WDM applications that the optical power in each sideband is near constant, necessitating the need to use additional spectral power flattening filters.

Another comb generator is described by Diddams et al in US 6,201,638 and the article "Broadband optical frequency comb generation with a phase-modulated parametric oscillator", Optics Letters vol.24 (23) pp.1747-1749 1999. The device reported by Diddams et al is a near-degenerate, doubly-resonant optical parametric oscillator. As is well known, an optical parametric oscillator includes a nonlinear crystal that is adapted

to convert pump wave radiation of a first frequency into two waves, typically referred to as the signal and the idler waves. The sum of the frequencies of the signal and idler waves is the frequency of the pump wave, and so
5 the signal and idler waves are sometimes collectively referred to as down-converted waves. By near-degenerate, doubly-resonant optical parametric oscillator, it is meant that the system proposed by Diddams et al is an optical parametric oscillator in which the signal and
10 idler wavelengths are substantially the same and that both are resonant within the optical cavity.

Using an active electro-optic phase modulator, Diddams et al reported a spectral extent to the comb generated of 5.6 THz, where the free spectral range of
15 the optical parametric oscillator was 350 MHz and the optical parametric oscillator was pumped by 500 mW of optical power at a pump wavelength of 532 nm. Due to all the generated signal and idler wavelength pairs being resonant modes of the optical parametric oscillator and
20 experiencing optical gain, the power spectrum of the generated comb is substantially flat. However, a problem with the device described by Diddams et al is that substantial external optical powers are required in the pump wave that is used to excite the optical parametric
25 generator in the first instance. Because such a necessity can require cumbersome pump wave generators, a considerable disadvantage can arise in relation to the application of such devices in the context of WDM, where efficient and compact sources overall are required for
30 the generation of frequency combs.

An object of the present invention is to provide a frequency comb generator that can be operated at relatively low power levels.

According to one aspect of the present invention there is provided a frequency comb generator comprising a pump enhanced degenerate or near degenerate optical parametric generator having a pump enhancement cavity and
5 a down-converted wave cavity, and a phase modulator that is positioned in the down-converted wave cavity.

By locating the nonlinear crystal of the optical parametric oscillator, in which the signal and idler waves are generated, in a cavity in which the pump wave
10 intensity is resonantly enhanced, the optical power from the pump wave generator that is required to pump the optical parametric generator is substantially reduced compared to the optical power required by present state of the art devices. This opens the opportunity to use the
15 comb generator in for example telecommunications applications.

Means may be provided for varying an optical length of the pump cavity, thereby to ensure that the resonant condition can be maintained. Likewise, means may be
20 provided for varying an optical length of the down-converted wave cavity.

In the arrangement in which the invention is embodied, the intensity of the pump wave within the nonlinear crystal of the optical parametric generator is
25 substantially increased above the intensity obtainable in the pump wave directly from the pump wave generator for similar conditions of beam geometry by placing the nonlinear crystal within an optical cavity that is held on-resonance at the frequency of the pump wave (pump wave
30 cavity), and into which cavity the optical power in the pump wave as generated by the pump wave generator is appropriately coupled. In this way the optical field intensity in the pump wave inside the optical cavity is made considerably greater than that attainable outside of

the aforesaid pump wave cavity under conditions of similar pump wave geometries.

The pump-enhancement geometry has previously been described and was first demonstrated in the context of continuous-wave optical parametric generators by G. Robertson et al "Continuous-wave singly resonant pump-enhanced Type II LiB3O5 optical parametric oscillator" Optics Letters 19 (21) pp.1735-1737 (1994). Since publication of this article, pump-enhancement arrangements have been studied by a number of investigators. However, this has not been used in the context of an optical parametric generator that is used for comb generation. The inventors have appreciated that by using the pump-enhanced optical parametric generator in combination with a phase modulator a practical frequency comb generator can be realised for application in for example WDM systems. The inventors have also appreciated that although the comb generator proposed by Diddams et al is doubly resonant, a singly resonant arrangement for a pump enhanced optical parametric oscillator can also be used.

Various aspects of the invention will now be described by way of example only and with reference to the accompanying drawing, i.e. Figure 1.

Figure 1 shows an optical parametric frequency comb generator. This comprises a pump-enhanced optical parametric oscillator 10, in which a phase modulator 12, which may be active or passive, is provided in the down-converted wave cavity. More specifically, the generator of Figure 1 has a laser pump arrangement 14 for pumping a non-linear medium 16 that is located within an oven 17 that is in a first optical cavity 18. The pump wave is coupled into the first optical cavity 18 by way of a lens 34, which is chosen so that the pump wave is mode-matched

into a transverse mode of the cavity. Typically, this is the fundamental mode of the cavity (TEM_{00}). Any suitable laser pump could be used, although preferably a semiconductor diode laser is employed. This is compact and efficient in converting electrical power into optical power. The pump wave generator has to generate radiation that is of high spectral purity, i.e. single longitudinal mode, and of high spatial quality, i.e. single transverse mode. In practice, this condition restricts the use of semiconductor diode lasers to those of a type typically limited to an output power of less than 200 mW.

The nonlinear medium 16 may be any suitable material, but a specific example is a crystal of periodically-poled lithium niobate. This has a grating period range associated with the periodic poling of 18.6 to 20.4 microns. When held at an appropriate temperature in the range 150 to 190 degrees C using the oven 17, then for radiation propagating along the x-axis and polarised linearly with electric vector along the z-axis, this material 16 down converts through the parametric generation process a pump wavelength of around 800nm (780-810 nm) into signal and idler waves with wavelengths around degeneracy, namely around 1600 nm. By degeneracy it is meant that both the signal and the idler wavelengths are substantially the same.

The first cavity 18, which is referred to as the pump wave cavity, is defined by first and second mirrors 20 and 22. Between the first and second mirrors 20 and 22 is a beam splitter 24 that is positioned so as to direct down-converted radiation emitted from the nonlinear medium 16 onto a third mirror 26. The second mirror 22 and the third mirror 26 define a second optical cavity 28, which is referred to as the down-converted wave cavity. Each of the first and second mirrors 20 and

22 is highly reflective at the wavelength of light emitted from the laser pump 14. The beam splitter 24 is highly transmissive at the pump radiation so that it allows light emitted from the pump 14 to pass through it and into the nonlinear material 16, whilst at the same time is highly reflective to down converted waves emitted from the nonlinear material 16 so as to reflect such radiation either onto the third mirror 26 or back into the nonlinear material 16. The second mirror 22 is wholly reflective at both the signal and idler wavelengths. The third mirror 26 is partially transmissive to all of the down-converted light emitted from the nonlinear material 16 so that an output can be gained. Output coupling through the third mirror 26 makes the design and fabrication of the second and third mirrors simpler.

The first and second mirrors 20 and 22 are positioned so that the pump cavity 18 is resonant at the pump wavelength. As is well known, to fulfil this condition, the separation of the mirrors, i.e. mirrors 20 and 22, that define the cavity 18 has to be an integer number of half wavelengths of the wave, in this case the pump wave. To ensure that a resonant condition can be maintained, connected to the first mirror 20 is a drive mechanism (not shown) that is able to move the mirror in a controllable manner. By controlling the drive mechanism using a suitable control system 30, the first mirror can be moved, so that the first cavity length is adjustable. In this way, it is possible to tune the cavity such that the frequency of the single frequency pump wave is an axial mode of the cavity, and so that this pump wave resonates within the cavity 18.

Causing resonance of the pump wave builds up the intensity of that wave inside the first cavity 18 to a

level that is above that of the incident pump wave, so that the pump wave is said to be enhanced. The pump wave intensity is typically increased by a factor of 10 or more. It should be noted that the transmission shown by
5 the first mirror 20 to the pump wave is generally chosen such that when the parametric oscillator is operating under the specified conditions then the pump cavity is impedance matched. This means that there is no back reflected pump wave from the first mirror 20 and all of
10 the incident pump wave enters the cavity 18, where apart from parasitic losses it is all converted into the signal and idler waves.

The second and third mirrors 22 and 26 are fabricated and positioned so that either one only of the
15 two down-converted waves is resonant (referred to as a singly-resonant oscillator), or both are simultaneously resonant (referred to as a doubly-resonant oscillator). In the former case the length of the cavity 28 is an integer number of half-wavelengths of the down-converted
20 wave that is resonant. In the latter case the length of the cavity 28 must be an integer number of half-wavelengths of both of the down-converted waves since both these waves must be simultaneously resonant. In general it will be the case that the integer is different
25 for one of the down-converted waves compared to the other.

It should be noted that when the non-linear material
16 is stimulated with the pump wave, a range of signal and idler wavelength pairs all having different
30 frequencies may be generated. However, only those frequencies that are resonant within the cavity experience optical gain through interaction with the pump wave in the nonlinear medium 16 and thus survive. All other non-resonant frequencies decay away. This means

that these generators self seek a resonant condition. By this it is meant that only those signal and idler frequencies that are resonant survive within the cavity, and so a resonant condition will automatically be generated. The significance of this is that the actual length of the down-converted wave cavity 28 is not critical in the case of the singly-resonant oscillator, because the generator will automatically self seek the singly resonant condition. However, in the case of the doubly-resonant oscillator there may in general be only certain specific spacings of mirrors 22 and 26 that simultaneously satisfy the required double resonance condition, given the further constraint that the sum of the signal and idler frequencies must equal the pump frequency.

By saying that the down-converted wave cavity 28 has to be an integer number of half wavelengths of either one of the down-converted waves in the case of the singly-resonant oscillator or both of the down-converted waves in the case of the doubly-resonant oscillator, it might be implied that the frequency of the down-converted wave has to be known to determine the spacing of the mirrors 22 and 26, thereby to meet a resonant condition. However, in practice the inverse is true, that is the resonant down-converted wave frequencies will be automatically chosen according to the provided optical path length of the cavity 28, but in the case of the doubly resonant oscillator this may only occur at certain specific spacings of the mirrors 22 and 26. It will be appreciated that a range of frequencies (the axial modes) can be resonant within the cavity, where the difference in frequency between each of the axial modes is known as the free spectral range frequency of the cavity, and is

equal to $c/2l$, where c is the speed of light and l is the optical length of the down-converted wave cavity 28.

Within the part of the down-converted wave cavity 28 that lies between the beamsplitter 24 and the third mirror 26, i.e. the section from which the pump wave is absent, is the phase modulator 12. The phase modulator is contained within a resonant RF cavity (not shown) in order to apply the required high frequency electrical fields necessary to attain modulation frequencies close to the frequency separation of the axial modes of the signal/idler wave cavity (in the present example 600 MHz). More specifically, the phase modulator 12 is driven by a radio frequency or microwave oscillator (not shown) at a frequency ν , where ν is an integer multiple of the down-converted wave cavity 28 free spectral range frequency. The phase modulator acts so as to transfer energy from the resonant frequencies of the down-converted waves, which as previously described are axial modes of the down-converted wave cavity 28, into two new sidebands at frequencies $f \pm \nu$, which are also axial modes of the down-converted wave cavity 28. These new frequencies are then also resonant within the optical cavity 28. This means that these sidebands are amplified in the nonlinear medium 16 and are re-circulated through the phase modulator 12 so producing secondary sidebands which in turn generate their own sidebands and so on. Under these conditions, one or more frequency combs can be generated.

Any suitable phase modulator may be used. As an example, however, the phase modulator 12 of Figure 1 is based on a crystal of lithium niobate. Alternate materials include crystal quartz, lithium tantalate and magnesium oxide doped lithium niobate. Between the modulator 12 and the beam splitter 24 is a lens 32, which

is included to provide additional flexibility in the control of the spatial mode of the down-converted waves in this part of the second cavity 28.

Because of the characteristics of the three mirrors 20, 22 and 26, the first and second optical cavities 18 and 28 formed around the nonlinear crystal 16 are optically independent. The first optical cavity 18 is arranged such that the pump wave resonates. Hence, the parametric oscillator is said to be pump-enhanced. The second cavity 28 is such that either one or both of the down-converted waves resonate. Hence, the parametric oscillator is said to be a singly-resonant or doubly-resonant oscillator respectively.

Typical performance figures associated with the device of Figure 1 are: threshold for oscillation of the parametric oscillator 20-40 mW at 800nm, typical pump enhancement at this threshold of 8-9 indicating an internal threshold of 250 mW, useable output power into the signal/idler comb of 12 mW when pumping at 3 times threshold indicating an external efficiency of around 13% (internal down-conversion efficiency around 60%), frequency comb generated over 60 nm, i.e. 7 THz, at 1600nm, with a mode spacing in the comb variable over 490-690 MHz, limited by the tuning range of the electro-optic modulator.

It will be appreciated that without active control of the position of the third mirror 26, the length of the second cavity 28 may be free to drift. This may cause a shift in the free spectral range frequency of the second cavity 28 and thus a mismatch between the free spectral range and the modulator frequency. Further the absolute position of the modes of the frequency comb in frequency space will also shift. Further in the case of the doubly-resonant oscillator the spacing of the cavity mirrors

must be such as to fulfil the previously-described doubly-resonant conditions as well as the constraint that the sum of the signal and idler frequencies for any particular signal/idler mode pair be equal to the pump frequency. To eliminate these problems, a second control system 36 is optionally provided for controlling the position of the third mirror 26. This system 36 incorporates a frequency reference standard (for example an atomic or molecular transition) for establishing the frequency of the comb. The measured frequency is fed back to the control system via a feedback loop. In the event that the comb and the reference frequencies are different, the control system is caused to vary the position of the third mirror 26, and so the length of the second cavity 28 until the desired frequency is realised. In this way it is possible to substantially fix the generated frequency comb in frequency space.

It will be further appreciated that the spectral extent of the comb generated is limited by dispersion in the optics of the second, that is the down-converted wave, cavity 28. In this example, the cavity 28 includes the phase modulator 12, nonlinear crystal 16 and the lens 32. The combined dispersion of these components results in a change in the optical length of the optical cavity 28, and so the free spectral range of the cavity, as a function of frequency. Consequently, as the spectral extent of the comb is broadened the longitudinal mode spacing of the optical cavity 28 does not match precisely the phase modulator 12 frequency, limiting further spectral broadening. It is recognised that within the system described dispersion compensation can be incorporated using a variety of techniques. A particular but not exclusive example of this is the application of a dispersion compensating multi-layer coating to the third

cavity mirror 26. Another example is the inclusion of additional dispersion compensating reflective elements 40 in the optical cavity 28 that compensate for the dispersion of the other optical elements and hence provide a substantially fixed optical cavity length and free spectral range. In the case of the doubly-resonant oscillator perfect dispersion compensation and thus all modes being equally spaced in frequency will ensure that all signal-idler mode pairs will become simultaneously resonant at each of the specific spacings of the cavity mirrors as afore described, hence contributing greatly to both the intensity and frequency stability of the generated comb.

The method of generating a comb of frequencies in which the invention is embodied uses an optical parametric generator that incorporates a phase modulator. Down-converted waves generated by the optical parametric generator may be produced as a comb of frequencies, either on one or the other of these waves separately, or on both simultaneously. In the latter case, where combs are created for both down converted waves, the signal and idler waves are preferably close enough together in frequency so that the two combs generated overlap, and so become in effect a single comb of frequencies such that all the frequencies in this single comb are now related to one another in the manner previously described above.

A skilled person will appreciate that variations of the disclosed areas are possible without departing from the invention. For example, whilst the use of a phase modulator has been described, it will be appreciated that other devices or means capable of generating sidebands could be used. Accordingly, the description of a specific embodiment is made by way of example only and not for the purposes of limitations.

35

Claims

1. A frequency comb generator comprising:
 - a nonlinear material, such as a nonlinear crystal,
 - 5 that produces two or more down-converted waves when optically stimulated using an optical pump;
 - a resonant pump cavity in which the pump wavelength is resonant, the nonlinear material being located in the resonant pump cavity;
 - 10 a down-converted wave cavity in which one or more of the down-converted waves is resonant, and
 - a phase modulator that is located in the down-converted wave cavity.
- 15 2. A frequency comb generator as claimed in claim 1, wherein the phase modulator is provided in a part of the down-converted wave cavity that is separate from the resonant pump cavity.
- 20 3. A frequency comb generator as claimed in claim 1 or claim 2, wherein the down converted waves have wavelengths that are the same or substantially the same.
4. A frequency comb generator as claimed in any of the
- 25 preceding claims, wherein the phase modulator is active or passive.
5. A frequency comb generator as claimed in any of the preceding claims, wherein the non-linear material
- 30 comprises a crystal of periodically-poled lithium niobate.

6. A frequency comb generator as claimed in claim 5, wherein the periodically poled crystal has a grating period range of 18.6 to 20.4 microns.

5 7. A frequency comb generator as claimed in any of the preceding claims further comprising an optical source for use as the optical pump.

8. A frequency comb generator as claimed in claim 7,
10 wherein the optical source is a semi-conductor diode laser.

9. A frequency comb generator as claimed in any of the preceding claims further comprising means for varying an
15 optical length of the pump cavity.

10. A frequency comb generator as claimed in any of the preceding claims further comprising means for varying an optical length of the down-converted wave cavity.

20

11. A frequency comb generator as claimed in any of the preceding claims further comprising means for compensating for dispersion in the down-converted wave cavity.

25

12. A frequency comb generator as claimed in claim 11, wherein dispersion compensation is provided by a reflective coating or coatings.

30 13. A frequency comb generator as claimed in claim 11 or claim 12, wherein dispersion compensation is provided by propagation of the down converted wave or waves through an optical material providing compensating dispersion for

the other optical components through which said wave or waves propagate.

14. A wavelength division multiplexer that includes a
5 comb generator as claimed in any of the preceding claims.

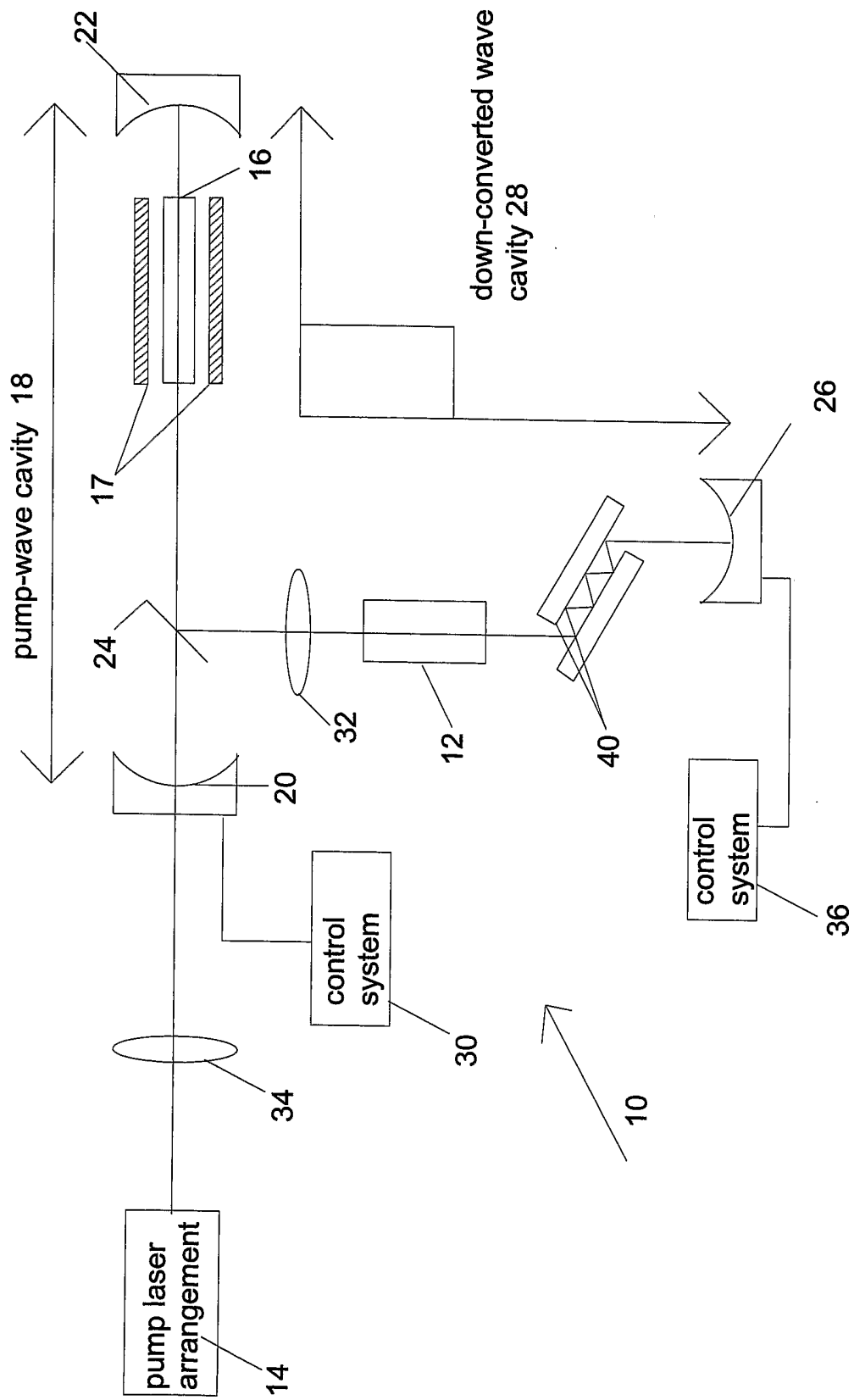


Figure 1

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INTERNATIONAL SEARCH REPORT

International Application No

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	MOTONOBU KOUROGI ET AL: "WIDE-SPAN OPTICAL FREQUENCY COMB GENERATOR FOR ACCURATE OPTICAL FREQUENCY DIFFERENCE MEASUREMENT" IEEE JOURNAL OF QUANTUM ELECTRONICS, IEEE INC. NEW YORK, US, vol. 29, no. 10, 1 October 1993 (1993-10-01), pages 2693-2701, XP000423090 ISSN: 0018-9197 cited in the application	1,2,4,5, 7-10
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