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Datasheet for the decision of 14 October 2013

Case Number: T 1735/10 - 3.4.02

Application Number: 07009067.5

Publication Number: 1988425

IPC: G02F1/39, H01S3/108

Language of the proceedings: EN

Title of invention:
Method and apparatus for optical frequency comb generation using a monolithic microresonator

Applicant:
Max-Planck-Gesellschaft zur Förderung
der Wissenschaften e.V.

Headword:

Relevant legal provisions:
EPC Art. 56

Keyword:
Inventive step - (yes)

Decisions cited:

Catchword:

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Case Number: T 1735/10 - 3.4.02

DECISION
of Technical Board of Appeal 3.4.02
of 14 October 2013

Appellant: (Applicant)	Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V. Hofgartenstrasse 8 80539 München (DE)
Representative:	Hertz, Oliver v. Bezold & Partner Patentanwälte Akademiestrasse 7 80799 München (DE)
Decision under appeal:	**Decision of the Examining Division of the European Patent Office posted on 22 March 2010 refusing European patent application No. 07009067.5 pursuant to Article 97(2) EPC.**

Composition of the Board:

Chairman:	A. Klein
Members:	F. Maaswinkel
	D. Rogers

Summary of Facts and Submissions

I. The appellant lodged an appeal against the decision of the examining division, refusing the European patent application 07009067.5. This patent application relates to optical frequency comb generation using a monolithic microresonator.

According to the decision, the subject-matter of claims 1 and 15 according to the Main Request and claim 1 according to the Auxiliary Request did not involve an inventive step within the meaning of Article 56 EPC having regard to the combination of the disclosures in document D1 and D3:

D1: PHYSICAL REVIEW LETTERS, vol. 93 no. 8 pages 083904/1 - 4, 20 August 2004; KIPPENBERG T J et al: "Kerr-nonlinearity optical parametric oscillation in an ultrahigh-Q toroid microcavity"
D3: WO-2005/122346.

II. With the letter containing the grounds of appeal the appellant requested to set aside the decision and to grant a patent on the basis of the sets of claims according to a Main or First Auxiliary Requests filed with this letter. The appellant also filed an auxiliary request for oral proceedings.

With a letter dated 10 July 2013 the appellant filed amended description pages 2a, 3, 4, 5.

III. The wording of independent claim 1 of the Main Request reads as follows:

" An optical frequency comb generator, comprising:
- a laser device being arranged for generating input laser light providing pump photons having a predetermined input light frequency,
- a dielectric monolithic micro-resonator having a cavity exhibiting a third order nonlinearity, so that the micro-resonator provides optical parametric generation based on four-wave mixing among two of the pump photons with a signal and an idler photon and providing parametrically generated light including signal and idler optical sidebands, and
- a waveguide optically coupled to the micro-resonator, the waveguide being arranged for in-coupling the input laser light into the micro-resonator and out-coupling the parametrically generated light out of the micro-resonator, wherein
- the laser device, the waveguide and the micro-resonator being arranged for resonantly in-coupling the input laser light to a mode of the micro-resonator, wherein
- the arrangement for resonant in-coupling the input laser light is such that the mode of the micro-resonator has at least such a power level that an optical field inside the cavity exceeds a predetermined cascaded parametric oscillation threshold at which the parametrically generated light includes at least 50 phase-coherent higher order sidebands relative to the input light frequency, said phase-coherent higher order sidebands having an equidistant mode spacing in frequency space,
- the micro-resonator is compensated for its dispersion, wherein a geometric dispersion and a material dispersion of the cavity at least partially cancel each other in a wavelength range spanned by the phase-coherent higher order sidebands,
- a detector device is arranged for detecting the mode

spacing between adjacent sidebands of the parametrically generated light, and
- a feedback loop is coupled with the detector device, the feedback loop being arranged for stabilizing the mode spacing by controlling at least one of temperature of the micro-resonator, strain on the micro-resonator, pump power of the input laser device, laser frequency of the input laser device and distance between waveguide and micro-resonator ".

The wording of independent claim 15 reads as follows:

" A method of generating an optical frequency comb, comprising the steps of:
- generating input laser light with a laser device, said input laser light providing pump photons having a predetermined input light frequency,
- coupling the input laser light via a waveguide into a dielectric monolithic micro-resonator having a cavity exhibiting a third order nonlinearity, wherein the waveguide includes an in-fiber polarization controller and the polarization of the pump photons is adapted to polarization dependent cavity resonances,
- providing parametrically generated light including signal and idler optical sidebands in the micro-resonator by optical parametric generation based on four-wave mixing among two of the pump photons with a signal and an idler photon, and
- coupling the parametrically generated light out of the micro-resonator, wherein
- the input laser light is coupled to a mode of the micro-resonator having at least a power level such that an optical field inside the cavity exceeds a predetermined cascaded parametric oscillation threshold at which the parametrically generated light includes at least 50 phase-coherent higher order sidebands of the

optical sidebands of the input light frequency, said phase-coherent higher order sidebands having an equidistant mode spacing in frequency space and said micro-resonator being compensated for its dispersion, wherein a geometric dispersion and a material dispersion of the cavity at least partially cancel each other in a wavelength range spanned by the phase-coherent higher order sidebands, and the method comprises the further steps of
- detecting the mode spacing between adjacent sidebands of the parametrically generated light with a detector device, and
- stabilizing the mode spacing using a feedback loop being coupled with the detector device and controlling at least one of temperature of the micro-resonator, strain on the microresonator, pump power of the input laser device, laser frequency of the input laser device and distance between waveguide and micro-resonator ".

Claims 2 to 14 and claims 16 and 17 are dependent claims.

The claims of the Auxiliary Request are not relevant for the purpose of the present Decision.

IV. The appellant's arguments may be summarised as follows:

The decision is based on a misinterpretation of documents D1 and D3 and an inappropriate application of the problem—solution approach. According to the decision, document D1 would disclose an optical comb generator. This view is not correct. The concept "optical comb generator" has a well defined technical meaning in the art, see the publication "Reviews of Modern Physics", Vol. 75, 2003, p. 325, S.T. Cundiff and Jun Ye "Colloquium: Femtosecond optical frequency combs". The term "optical frequency comb" is a frequency domain description of pulsed optical electromagnetic radiation (*pulsed laser light*), which is composed of a plurality of frequency components. In the time domain description, the optical frequency comb is a sequence of light pulses. Thus, an optical frequency comb and pulsed laser light represent synonyms describing the same physical phenomenon. Although the term "optical frequency comb" is not quantitatively defined in terms of a minimum number of comb frequencies, yet, with a reduction of the laser pulse duration, the number of required comb frequencies increases. Conversely, with a reduction of the number of comb frequencies, the pulse duration increases, leading to the loss of the pulse shape in the time domain. Therefore, if only a few comb frequencies exist, e.g. the five peaks shown in Fig. 3 of document D1, these do not correspond to light pulses, but represent a continuous light field with some amplitude modulation. In other words, a sequence of only a few frequencies is not a frequency comb. A further important feature of frequency combs is their flat optical spectrum, i.e. the components have similar amplitudes. This feature results from the Fourier transformation based time-frequency correspondence of pulses and a frequency comb. Hence, the oscillation spectrum shown in Figure 3 of document D1 does not correspond to an optical frequency comb since, firstly, a spectrum consisting of only five components in the frequency domain corresponds to a continuous temporal signal and not to a sequence of light pulses; and secondly, since the first (Idler; Signal) and the subsidiary (I'; S') components do not have similar amplitudes, rather the subsidiary peaks are approximately 25dBm below the signal and idler modes.

Therefore, contrary to the reasoning in point 2 of the decision, document D1 does not disclose an optical frequency comb generator. Furthermore, in the decision it was alleged that document D1 would disclose a cascaded parametric oscillation. The "cascade" concept implies that a power level is obtained wherein parametric oscillation side bands create higher order sidebands which again create higher order side bands (see general meaning of the term "cascade" in print—out from the online Merriam-Webster dictionary filed on February 1, 2010). Document D1 suggests an explanation of the appearance of the higher-order sidebands I' and S' (see Figure 3) as a combination of non—linear effects, such as parametric oscillation of the signal and idler bands. The parametric frequency conversion of the signal and idler bands results in the higher-order sidebands. However, the higher-order sidebands I', S' do not create additional sidebands, therefore a "cascade" effect is not disclosed. Finally, in the decision it was argued with reference to the symbol $\Delta\nu_{FSR}$ in Figure 3 of D1 that the higher-order sidebands would have an equidistant mode spacing $\Delta\nu_{FSR}$. Still, this conclusion may not be drawn from this Figure, since in order to ensure that the mode spacing is equidistant the absolute frequencies of the spectrum should have been measured with high precision, for which the publication D1 gives no information whatsoever. On the contrary, document D1 explicitly discloses that an irregular spacing of the frequencies was expected (*see page 083904-1, rhc, 1.1 and 2*).

Document Dl is considered as the closest prior art document. Although it does not disclose a frequency comb generator, the experiment described in document Dl is considered as a proper starting point of the invention, because it has more similarities with the

claimed invention than the disclosures of the other cited documents. The subject-matter of claims 1 and 15 differ from the disclosure in document D1 in the following features:
(a) An optical frequency comb generator and a method of generating a comb generator;
(b) The laser device, the waveguide and the micro-resonator have a certain coupling arrangement, which is selected such that a power level in the cavity exceeds a cascaded parametric oscillation threshold yielding at least 50 frequency components;
(c) The micro-resonator is compensated for its dispersion;
(d) A detector device is provided for detecting the mode spacing between sidebands of the parametrically generated light; and
(e) A feedback loop is provided for stabilizing the mode spacing.

As discussed before, feature (a) is not disclosed in D1. The novelty of features (b) to (e) has been acknowledged in point 2.1 of the decision. These differences (a) to (e) address the technical problem of providing an optical frequency comb generator (*claim 1*), respectively providing a method of generating an optical frequency comb using a micro—resonator having a cavity exhibiting a third order nonlinearity (*claim 15*).

From the above discussion of document D1, in particular concerning Figure 3, it is clear that this document neither discloses nor suggests to provide the new features for solving the above technical problem. Based on the discussion in D1 that the resonant frequencies would be irregularly spaced due to cavity and material dispersion (*page 083904-1*) and observing the experimentally found decreased amplitudes of the higher-order sidebands of 25dBm, the skilled person would not expect that a frequency comb can be generated with the experimental arrangement of document D1.

Furthermore, the skilled person would not consider a combination of documents D1 and D3, since document D3 does not disclose the creation of an optical frequency comb. Document D3 is not related to the above technical problem. The only reference to a frequency comb generator in document D3 is the theoretical statement in para [0073] referring to a method which does not exist in practice. There is no reason that a skilled person would consider an Opto-Electronic Oscillator as disclosed in D3 for solving the above technical problem, since the parametric oscillations disclosed in document D1 and the opto-electrical oscillations disclosed in document D3 represent essentially different mechanisms. Although the cavity material silica is disclosed in both documents, different optical effects are used with both techniques. The technique of document D3 does not use non-linear optical parametric oscillations. This document discloses that it is technically difficult, if not impossible, to achieve equal mode spacing in uniform index resonators, and that graded index resonators can be used in order to produce an equal mode spacing. However, document D3 is silent with regard to any idea of providing an equal mode spacing in a frequency range, which would allow the generation of a frequency comb, i.e. in a broad frequency range covering at least 50 equally spaced comb modes. Paragraph [0073] of D3 mentions that such a micro-resonator is not available.

In the decision, page 7, para 3 and 4, it had been argued that the features defining the dispersion compensation and the detector device/feedback loop would merely represent an aggregation. This is not correct: with the dispersion compensation (*feature (c)*), a broad frequency range is provided wherein the optical frequency comb comprising at least 50 equally spaced comb modes can be created. Without the dispersion compensation, the feedback loop would not function. The feedback loop (*features (d) and (e)*) provides a kind of tuning of the resonator modes within the frequency range obtained with the dispersion compensation. Therefore the combination of these features involves a functional interaction, enabling the generation of an optical comb with at least 50 frequency components with equidistant mode spacing. Since neither document D1 nor document D3 disclose or suggest such an optical frequency comb generator, the subject-matter of the independent claims of the Main Request is novel and equally involves an inventive step.

Reasons for the Decision

1. The appeal is admissible.

2. Amendments

In the decision no objections under Article 84 EPC or 123(2) EPC 1973 against the documents then on file were raised. The board sees no reason of its own to disturb this finding.

The set of claims according to the Main Request only differs from the previous version by being cast in the one-part form, see Rule 43(1) EPC and page 244 of Case Law of the Boards of Appeal, 7nd ed.

According to the appellant, this is the more appropriate form, since the closest prior art document D1 does not disclose a frequency comb generator.

3. *Patentability*

3.1 *Novelty - Claim 1*

3.1.1 According to the decision, document D1 disclosed an optical parametric oscillator. It was recognised that the subject-mater of the claims was novel over the disclosure in this document.

3.1.2 More in particular in the parametric oscillator arrangement disclosed in document D1 the following technical features of claim 1 could be identified:
- a laser device being arranged for generating input laser light providing pump photons having a predetermined input light frequency;
- a dielectric monolithic micro-resonator having a cavity exhibiting a third order nonlinearity, so that the micro-resonator provides optical parametric generation based on four-wave mixing among two of the pump photons with a signal and an idler photon and providing parametrically generated light including signal and idler optical sidebands; and
- a waveguide optically coupled to the micro-resonator, the waveguide being arranged for in-coupling the input laser light into the micro-resonator and out-coupling the parametrically generated light out of the micro-resonator, wherein
- the laser device, the waveguide and the micro-

resonator being arranged for resonantly in-coupling the input laser light to a mode of the micro-resonator.

It is noted that these features were also defined in the preamble of the previous version of this claim (*which was cast in the two-part form*), thereby acknowledging that these features were known from the device addressed in document D1.

3.1.3 By making reference to the parametric oscillation spectrum shown in Figure 3 of this document the examining division observed that as a result of the nonlinear parametric interaction "at least four sidebands of the pump wavelength (signal, idler and subsidiary peaks S' and I') are generated in the device of D1 at four new wavelengths so as to form a comb of four parametrically-generated optical frequencies" and concluded "It can therefore be affirmed that the device of D1 is an optical comb generator" (*paragraph connecting page 5 and 6 of the decision*).

3.1.4 In the letter containing the grounds of appeal the appellant has contested that the spectrum shown in Figure 3 of document D1 allows to draw the conclusion that the device of D1 is an optical frequency comb generator. According to the appellant this concept has a well defined meaning in the art, making reference to the publication in "Reviews of Modern Physics" by Cundiff and Ye.

In Section I. "Introduction" of this publication it is disclosed: "The central concept to these advances is that the pulse train generated by a mode-locked laser has a frequency spectrum that consists of discrete, regularly spaced series of sharp lines, known as a frequency comb" (*page 325, rhc, 2nd para*). In the subsequent paragraph it reads: "(The idea that) a regularly spaced train of pulses corresponds to a comb in the frequency domain...".

At page 329, Section D. "Femtosecond optical frequency comb generator" of this publication, the first sentence reads: "A frequency comb generator produces a spectrum that consists of a series of equally spaced sharp lines with known frequencies".

Therefore an optical frequency comb generator exhibits a frequency spectrum consisting of discrete, regularly spaced series of sharp lines and, conversely, has a regularly spaced train of pulses in the time domain.

3.1.5 Although the above definition does not quantitatively specify a number of spectral features in order that the spectrum will correspond to a frequency comb, from the concept of "optical frequency comb" it may be understood that it is essential that an optical frequency comb signal should exhibit the series of pulses-behaviour both in the time as well as in the frequency domain. A further requirement is that the components (*both the spectral peaks as well as the time pulses*) must have similar or at least comparable amplitudes. This may be understood by Fourier-transforming the frequency spectrum to the time-domain or vice versa: clearly, only the respective components of similar amplitudes will contribute to the Fourier-transformed signal.

3.1.6 In the example in dispute, the spectrum in Figure 3 of document D1, the Idler (I) and Signal (S) components are at approximately 20dBm below the Pump spectral component. The further subsidiary peaks I', S' are at a level 25dBm further below the Idler and Signal amplitudes, i.e. these have only 0.003 times the amplitudes of the Idler and Signal components (*and, furthermore, are at 45dBm below the pump amplitude, i.e.* $3x10^{-5}$). Hence, by Fourier-transforming this spectrum, it follows that the subsidiary peaks I' and S' effectively do not contribute to the transformed time signal, which therefore consists of a high-frequency carrier wave at the frequency of the pump wave ω_p, amplitude-modulated by two much lower frequency waves at frequencies $\Delta\omega = 2\pi\Delta\nu_{FSR}$. Hence, if Fourier transformed, the spectrum in Figure 3 of document D1 does not represent a regular train of pulses but an amplitude-modulated continuous wave in the time domain and it therefore does not correspond to an optical frequency comb within the meaning accepted in the technical field.

3.1.7 Therefore the parametric oscillator arrangement disclosed in document D1 is not an optical frequency comb generator.

3.1.8 The subject-matter of claim 1 furthermore differs from the arrangement disclosed in document D1 by the features labelled (b) to (e) in the appellant's arguments (*see Section IV supra*). In point 2.1 of the decision the novelty of these features had been acknowledged by the examining division.

Hence, the subject-matter of claim 1 is novel over the disclosure in document D1.

3.1.9 Document D3 discloses an opto-electronic oscillator which does not involve parametric oscillations but uses optical modulation to produce oscillations in a frequency spectral range.

3.1.10 It is concluded that the subject-matter of claim 1, and similarly of claim 15, is novel (Art. 52(1) and 54 EPC).

3.2 Inventive step

3.2.1 In the decision the starting point for the discussion of inventive step was document D1, which, according to the examining division, disclosed an optical frequency comb generator. According to the decision, the technical features in claim 1 not disclosed in document D1 solved two technical problems, namely the increase of the number of equally-spaced sidebands and the control of the repetition rate of the optical frequency comb generator.

As set out in points 3.1.3 - 3.1.7 *supra* the board has established that the parametric oscillator arrangement in document D1 does not represent an optical frequency comb generator. Therefore the basic assumption of the discussion of inventive step in the decision is invalid, which is why the board does not concur with the reasoning in the decision.

3.2.2 According to the appellant, the technical problem addressed in the present patent application may be seen in providing an optical frequency comb generator.

3.2.3 In the opinion of the board it appears questionable whether a skilled person, without prior knowledge of the invention, would, after having taken notice of document D1, realise that the experimental results presented there could advantageously be implemented for constructing an optical frequency comb generator. It is noted that the gist of document D1 resides in the observation of Kerr-nonlinearity optical parametric oscillation in an ultrahigh-Q toroid microcavity, see the title of D1. In particular it is emphasised that by geometrical control of the microcavity, optical parametric oscillation can be observed at record low threshold levels, more than two orders of magnitude lower than for optical-fiber-based optical parametric oscillation, see the Abstract of this publication. The board has not found any clues or hints in document D1 that these experimental results could form the basis on which an optical frequency comb generator could be designed. Furthermore the board has not found any other prior art document cited in the examining proceedings teaching that an optical frequency comb generator could be constructed by applying the technique of optical parametric oscillation in a microcavity. Therefore, in the opinion of the board, starting from the disclosure in document D1 the technical problem should be formulated in a less ambitious way and without direct reference to optical frequency combs, for instance, in the problem addressing practical applications of optical parametric oscillation in toroid microcavity devices.

3.2.4 In any case, the board concurs with the appellant that document D1 would not lead the skilled person to modify the arrangement disclosed therein so as to obtain an optical frequency comb generator: as repeatedly expressed in the citations of the publication of Cundiff and Ye (*see point 3.1.4 supra*), it is an intrinsic feature of an optical frequency comb that the frequency spectral components (as well as the time pulses) are regularly (*i.e. equally*) spaced. On the other hand document D1, page 083904-1, first two lines, discloses that "...the resonant frequencies are, in general, irregularly spaced due to both cavity and material dispersion" (*underscore by the board*). The examining division reasoned that the indication of the Free Spectral Range in Figure 3 of D1 by the symbol $\Delta\nu_{FSR}$ was a proof of the equidistant mode spacing. However, it is understood that this symbol is only an indication for the separation of the signal and idler modes from the pump wavelength (*see the caption of Figure 3: "...twice the free spectral range 2x7.6nm"*) and no values are disclosed for the further components I' and S', moreover no precise measurement results are disclosed which could corroborate that the spectral peaks are indeed regularly spaced.

3.2.5 Hence, the spectrum shown in Figure 3 of document D1 only discloses two subsidiary peaks I' and S' at an amplitude level considerably (-25dBm) below the amplitudes of the Idler and Signal component and at a level further -20dBm below the pump. Furthermore, a regular spacing of the spectral components is not addressed, rather such a regular spacing "is not expected".

3.2.6 The technical features enabling the claimed device to function as an optical frequency generator are defined in the features labelled (b) to (e) in Section IV *supra*.

Document D1 does not give the skilled person any motive to modify its optical parametric arrangements so as to obtain these features and hence to obtain an optical frequency comb generator.

3.2.7 Neither would the skilled person, in the opinion of the board, find a solution of the technical problem of modifying the arrangement in D1 to an optical frequency comb generator in document D3: apart from the fact that the arrangement in D3 also includes a whisperinggallery mode resonator ("WGM"), the basic principle underlying this disclosure is rather different from that of document D1 (*opto-electronic oscillator versus optical parametric oscillator*).

In para [0073] of document D3 it is expressed in general terms that a WGM dielectric resonator with an equidistant spectrum may be used in frequency comb generators. However, apparently this proposal is rather speculative because, according to the preceding sentence in this paragraph, "the performance and range of applications based on WGM microcavities can be significantly expanded if a method is found to make microresonator modes equally spaced with precision corresponding to a fraction of the resonance bandwidth of a WGM resonator" (*emphasis by the board*). Document D3 does not disclose or suggest such a method, hence also a combination of the teachings of documents D1 and D3 would not lead to the subject-matter of claim 1 in an obvious way.

3.2.8 Therefore the subject-matter of claim 1 is novel and involves an inventive step.

3.2.9 Claim 15 is directed to a method of generating an optical frequency comb carried out in a device with the technical features of the comb generator defined in claim 1. Since the arrangement defined in claim 1 is novel and inventive the same applies to a method of generating an optical frequency comb.

3.2.10 Claims 2 to 14 and claims 16 and 17 are dependent claims and are equally allowable.

4. For the above reasons, the board finds that the appellant's Main Request meets the requirements of the EPC and that a patent can be granted on the basis thereof.

Order

For these reasons it is decided that:

1. The decision under appeal is set aside.

2. The case is remitted to the first instance with the order to grant a patent based on the following documents:

Claims: 1 to 17 of the Main Request, filed with the letter dated 21 July 2010;
Description: pages 1, 7 to 10, 12 to 15, 17 to 24 as originally filed;
pages 2, 6 and 16, filed with the letter of 4 November 2009;
pages 2a, 3, 4, 5 and 11, filed with the letter of 10 July 2013;
Drawings: sheets 1/8 to 8/8, as originally filed.

The Registrar: The Chairman:

Beschwerdekammern des Europäischen Patentamts ✦ Boards of Appeal of the European Patent Office ✦ Chambres de recours de l'Office européen des brevets

.A Counillon A. G. Klein

Decision electronically authenticated