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(54) **Title:** NANOPHOTONIC SPECTRAL TRANSLATION OF ELECTRO-OPTIC FREQUENCY COMBS

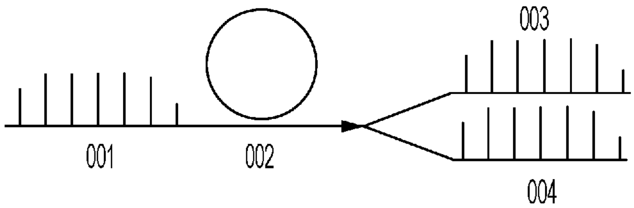


FIG. 1

(57) **Abstract:** The present invention is electro-optic frequency comb which can serve as a pump laser to a nonlinear microresonator. The teeth of the frequency comb of the present invention are efficiently transferred to one or more spectrally translated frequency combs across much of the visible and near-infrared spectral region.

WO 2025/038557 A1

NANOPHOTONIC SPECTRAL TRANSLATION OF ELECTRO-OPTIC FREQUENCY COMBS

Related Applications

This application claims the benefit of U.S. Provisional Patent Application Serial No. 63/532,300 (filed August 11, 2023), which is herein incorporated by reference in its entirety.

Federally-Sponsored Research and Development

This invention was made with United States Government support from the National Institute of Standards and Technology (NIST), an agency of the United States Department of Commerce. The Government has certain rights in this invention.

Background

The on-chip generation of coherent light across the visible and near-infrared wavelength regions has been a long-standing challenge in nanophotonics and would offer wide-spread use in areas such as optical metrology, communications, and integrated optics. While there is ongoing work on development of heterogeneously integrated lasers for accessing these wavelength ranges, developments in nonlinear nanophotonics provide another route to accessing wavelengths of interest.

Nonlinear microresonators have shown tremendous potential for chip-scale coherent wavelength access through, for example, optical parametric oscillation (OPO). *See* Lu *et al.*, "On-chip optical parametric oscillation into the visible: generating red, orange, yellow, and green from a near-infrared pump," Optica 7, 1417-1425 (2020). However, while the OPOs may be tuned both thermally and by varying the optical pump wavelength, reliably reaching narrow atomic transitions and performing spectroscopy – a prerequisite for the use of this technology in many applications – has proven challenging.

Brief Description

While nonlinear microresonators have been investigated for their use in nanophotonics, the use and tuning of, for example, optical parametric oscillation to reliably reach narrow atomic transitions or perform spectroscopy has proven challenging and is the subject of ongoing investigation. This invention is directed to an apparatus using an electro-optic frequency comb as the pump laser used with a nonlinear microresonator to output one or more spectrally translated frequency combs.

This invention is further directed to processes utilizing a frequency comb pump laser with nonlinear microresonators resulting in the robust and efficient generation of at least one spectrally translated frequency comb. This invention is further directed to the use of said spectrally translated frequency combs in spectroscopy.

Brief Description of the Drawings

The following description cannot be considered limiting in any way. Various objectives, features, and advantages of the disclosed subject matter can be more fully appreciated with reference to the following detailed description of the disclosed subject matter when considered in connection with the following drawings, in which like reference numerals identify like elements.

FIG. 1 shows a nonlinear microresonator converting a frequency comb pump laser into a one or more spectrally translated frequency combs and a depleted pump frequency comb.

FIG. 2 shows an example apparatus using an OPO in greater detail, with an external cavity diode laser (ECDL) passed through an electro-optic phase modulator (EOM) driven by a frequency chirp generated by a direct digital synthesizer (DDS), resulting in an electro-optic comb sent through a tapered amplifier (Amp) and then into a nanophotonic OPO resulting in translated signal and idler combs, as well as a depleted pump comb.

FIG. 3 shows results of an OPO system in greater detail, where $\chi^{(3)}$ optical parametric oscillator spectrally translates a pump electro-optic comb centered at ν_p, resulting in signal comb centered at ν_s, idler comb centered at ν_i, and the original pump comb at ν_p as outputs of the OPO.

FIG. 4 shows the spectral translation of an optical frequency comb over a wide spectral range as well as higher resolution images which show the flat envelop of the spectrally translated signal and idler combs.

FIG. 5 shows the proportion of total optical power found in the negative order comb teeth, carrier tone, and positive order comb teeth for an OPO system, with the OPO pump (at 780 nm) before and after the tapered amplifier and after the microring chip, as well as for the idler (at 877 nm) demonstrating that the OPO efficiency is preserved.

FIG. 6 and FIG. 7 show example measured beat notes between the electro-optic frequency comb teeth for the pump comb (780 nm) and idler comb (877 nm). For each of the detunings, the idler and pump linewidths agree to within their combined standard uncertainties and represent the limit on the spectral resolution of the tested laser source, demonstrating that the linewidth of the translated comb is preserved.

DETAILED DESCRIPTION

A detailed description of one or more embodiments is presented herein by way of exemplification and not limitation.

The construction and use of nanophotonic ring resonator-based optical parametric oscillators (OPOs) for translation of lasers or other emitted light into useful spectrums with some degree of precision has been disclosed. *See* Stone, Jordan et al. "Wavelength-Accurate Nonlinear Conversion through Wavenumber Selectivity in Photonic Crystal Resonators." *arXiv preprint arXiv:2212.05695* (2022). It has been discovered that that utilizing an electro-optic frequency comb as the pump laser to nonlinear microresonators, including OPOs, allows for robust and efficient generation of spectrally translated frequency combs. This allows for the on-chip conversion of optical frequency combs over a wide wavelength range in the visible and near-infrared, including at wavelengths where electro-optic modulators are not readily available.

It has been discovered that the resulting spectrally translated frequency combs alleviate the need for fine wavelength tuning of the nonlinear microresonators, allowing for spectroscopy on narrow atomic transitions to be readily performed with frequency agile combs.

Traditionally, the pump laser is a continuous-wave (CW) source with a linewidth much narrower than the cavity resonance; hence, in this case the OPO emits CW signal and idler waves. Modelling of the intracavity nonlinear dynamics indicates that phase modulation of the pump laser (the process creating the electro-optic frequency comb) is coherently mapped to the signal and idler waves if the modulation is sufficiently slow compared to the cavity photon lifetime, even in a strongly-driven regime where the residual carrier power is below the threshold for parametric oscillation. Such mapping underlies the coherent spectral translation of electro-optic frequency combs that we report here with regard to OPOs.

It has been discovered that unlike recently reported results on electro-optic comb conversion in a macroscale singly resonant OPO, in this invention the comb is transferred to both the signal and idler outputs. Such discovery also supports the use of various waveforms as being usefully preserved when modified by an OPO.

In an embodiment, with reference to FIG. 1, includes:

An electro-optic frequency comb serving as a pump laser [001] fed into a nonlinear microresonator [002] resulting in a spectrally translated frequency comb [003] and a depleted pump frequency comb [004].

In one embodiment, the nonlinear microresonator [002] is an optical parametric oscillator (OPO).

In one embodiment, the OPO results in two spectrally translated frequency combs: a signal comb, and an idler comb.

In one embodiment, the OPO is a Si_3N_4 microring relying on third-order ($\chi^{(3)}$) nonlinearity. In this system, pump frequency ν_p and the microring dispersion determines the signal and idler mode pair. The signal and idler waves with frequencies ν_s and ν_i, respectively, obey the energy conservation condition $2\nu_p = \nu_s + \nu_i$.

In one embodiment, the use of $\chi^{(3)}$ OPO provided flexible wavelength access while only requiring a single input laser.

In one embodiment, the signal and idler frequency comb pairs are used in performing spectroscopy.

In one embodiment, the signal and idler frequency comb pairs are used in performing measurements at nanosecond timescales.

In one embodiment, a source frequency comb is in optical communication with a nonlinear microresonator. Said nonlinear microresonator is further in optical communication with a detector. Means for passing a signal through an analyte may be disposed between the nonlinear microresonator and the detector.

In one embodiment, the nonlinear microresonator [002] is a second order $\chi^{(2)}$ OPO.

In one embodiment, the nonlinear microresonator [002] is configured for spectral translation of the pump frequency comb by pure $\chi^{(2)}$ second harmonic generation.

In one embodiment, the nonlinear microresonator [002] is configured for spectral translation of the pump frequency comb by photoinduced $\chi^{(2)}$ effects, including but not limited to second harmonic generation, sum frequency generation and difference frequency generation.

In one embodiment, the nonlinear microresonator [002] is configured for spectral translation of the pump frequency comb by electric field-induced $\chi^{(2)}$ behavior in a $\chi^{(3)}$ system.

In one embodiment, the nonlinear microresonator [002] is configured for spectral translation of the pump frequency comb by sum frequency generation.

In one embodiment, the nonlinear microresonator [002] is configured for spectral translation of the pump frequency comb by difference frequency generation.

In one embodiment, the nonlinear microresonator [002] is configured for spectral translation of the pump frequency comb by stimulated four-wave mixing.

In one embodiment, the nonlinear microresonator [002] is configured for spectral translation of the pump frequency comb by four-wave mixing Bragg scattering.

In one embodiment, the nonlinear microresonator [002] is configured for spectral translation of the pump frequency comb by Kerr comb generation.

In one embodiment, the nonlinear microresonator [002] is configured for spectral translation of the pump frequency comb by third or higher order harmonic generation.

In one embodiment, the nonlinear microresonator [002] is configured for spectral translation of the pump frequency comb by cascading of some combination of the above-described processes.

While one or more embodiments have been shown and described, modifications and substitutions may be made thereto without departing from the spirit and scope of the invention. Accordingly, it is to be understood that the present invention has been described by way of illustrations and not limitation. Embodiments herein can be used independently or can be combined.

All ranges disclosed herein are inclusive of the endpoints, and the endpoints are independently combinable with each other. The ranges are continuous and thus contain every value and subset thereof in the range. Unless otherwise stated or contextually inapplicable, all percentages, when expressing a quantity, are weight percentages. The suffix (s) as used herein is intended to include both the singular and the plural of the term that it modifies, thereby including at least one of that term (e.g., the colorant(s) includes at least one colorants). Option, optional, or optionally means that the subsequently described event or circumstance can or cannot occur, and that the description includes instances where the event occurs and instances where it does not. As used herein, combination is inclusive of blends, mixtures, alloys, reaction products, collection of elements, and the like.

As used herein, a “nonlinear microresonator” is a monolithic resonant cavity comprised of a material that possesses an optical nonlinearity, such as a second-order or third-order nonlinearity. Example nonlinear microresonator geometries include: structures made on integrated photonics chips, such as microring, microdisk, and photonic crystal cavities; and micromachined structures fashioned out of bulk materials, including microspheres and crystalline whispering gallery mode resonators. Characteristic length scales for nonlinear microresonators can be from the sub-micrometer scale to the millimeter-scale.

As used herein, a combination thereof refers to a combination comprising at least one of the named constituents, components, compounds, or elements, optionally together with one or more of the same class of constituents, components, compounds, or elements.

All references are incorporated herein by reference.

The use of the terms “a,” “an,” and “the” and similar referents in the context of describing the invention (especially in the context of the following claims) are to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context. It can further be noted that the terms first, second, primary, secondary, and the like herein do not denote any order, quantity, or importance, but rather are used to distinguish one element from another. It will also be understood that, although the terms first, second, etc. are, in some instances, used herein to describe various elements, these elements should not be limited by these terms. For example, a first current could be termed a second current, and, similarly, a second current could be termed a first current, without departing from the scope of the various described embodiments. The first current and the second current are both currents, but they are not the same condition unless explicitly stated as such.

The modifier about used in connection with a quantity is inclusive of the stated value and has the meaning dictated by the context (e.g., it includes the degree of error associated with measurement of the particular quantity). The conjunction or is used to link objects of a list or alternatives and is not disjunctive; rather the elements can be used separately or can be combined together under appropriate circumstances.

CLAIMS

What is claimed is:

1. An apparatus for the generation of a spectrally translated frequency comb comprising:

an electro-optic frequency comb source; and

a nonlinear microresonator in optical communication with the electro-optic frequency comb source;

wherein the electro-optic frequency comb source generates a pump frequency comb which is injected into the nonlinear microresonator, and wherein the nonlinear microresonator outputs at least one spectrally translated frequency comb and a depleted pump frequency comb.

2. The apparatus of claim 1, wherein the electro-optic frequency comb source comprises:

a laser source;

an electro-optic phase modulator in optical communication with the laser source;

a frequency source configured to drive the electro-optic phase modulator.

3. The apparatus of claim 1, wherein the nonlinear microresonator is an optical parametric oscillator (OPO).

4. The apparatus of claim 3, wherein the OPO outputs two spectrally translated frequency combs: a signal comb, and an idler comb.

5. The apparatus of claim 3, wherein the OPO is a Si_3N_4 microring relying on third-order ($\chi^{(3)}$) nonlinearity.

6. The apparatus of claim 3, wherein the OPO is a microring relying on second-order ($\chi^{(2)}$) nonlinearity.

7. The apparatus of claim 1, wherein the nonlinear microresonator is configured for spectral translation of the pump frequency comb by pure $\chi^{(2)}$ second harmonic generation.

8. The apparatus of claim 1, wherein the nonlinear microresonator is configured for spectral translation of the pump frequency comb by photoinduced $\chi^{(2)}$ effects.

9. The apparatus of claim 1, wherein the nonlinear microresonator is configured for spectral translation of the pump frequency comb by electric field-induced $\chi^{(2)}$ behavior in a $\chi^{(3)}$ system.

10. The apparatus of claim 1, wherein the nonlinear microresonator is configured for spectral translation of the pump frequency comb by sum frequency generation.

11. The apparatus of claim 1, wherein the nonlinear microresonator is configured for spectral translation of the pump frequency comb by difference frequency generation.

12. The apparatus of claim 1, wherein the nonlinear microresonator is configured for spectral translation of the pump frequency comb by stimulated four-wave mixing.

13. The apparatus of claim 1, wherein the nonlinear microresonator is configured for spectral translation of the pump frequency comb by four-wave mixing Bragg scattering.

14. The apparatus of claim 1, wherein the nonlinear microresonator is configured for spectral translation of the pump frequency comb by Kerr comb generation.

15. The apparatus of claim 1, wherein the nonlinear microresonator is configured for spectral translation of the pump frequency comb by third or higher order harmonic generation.

16. The apparatus of claim 1, wherein the nonlinear microresonator is configured for spectral translation of the pump frequency comb by the cascading of some combination of spectral translation processes.

17. A method for generating a spectrally translated frequency comb, the method comprising:

generating an electro-optic frequency comb (a pump frequency comb);

injecting the pump frequency comb into a nonlinear microresonator; and

creating at least one spectrally translated frequency comb as an output of the nonlinear microresonator.

18. The method of claim 17, wherein the nonlinear microresonator is an an optical parametric oscillator (OPO).

19. The method of claim 18, wherein the OPO outputs two spectrally translated frequency combs: a signal comb and an idler comb.

20. The method of claim 19, wherein the signal comb and idler comb are used in performing spectroscopy.

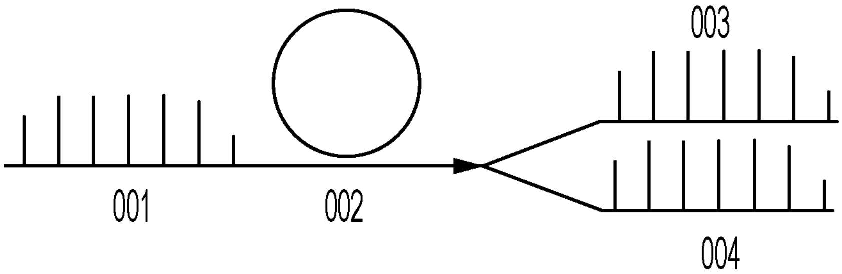


FIG. 1

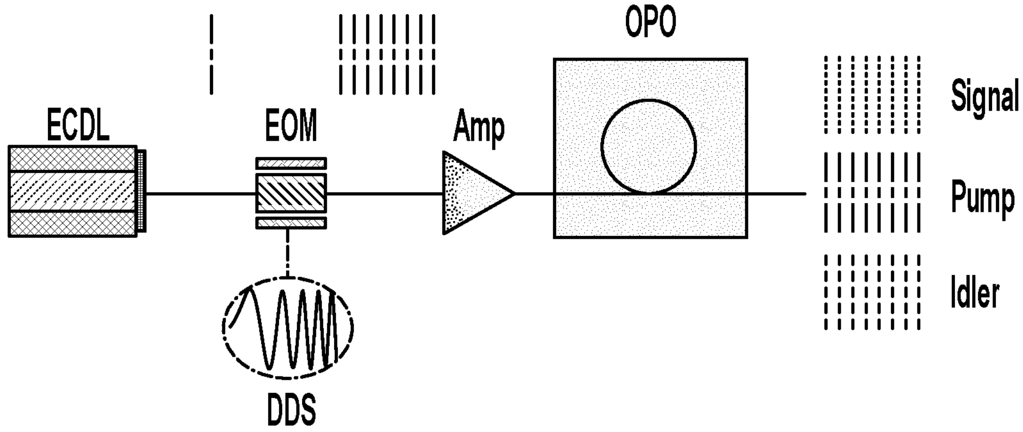


FIG. 2

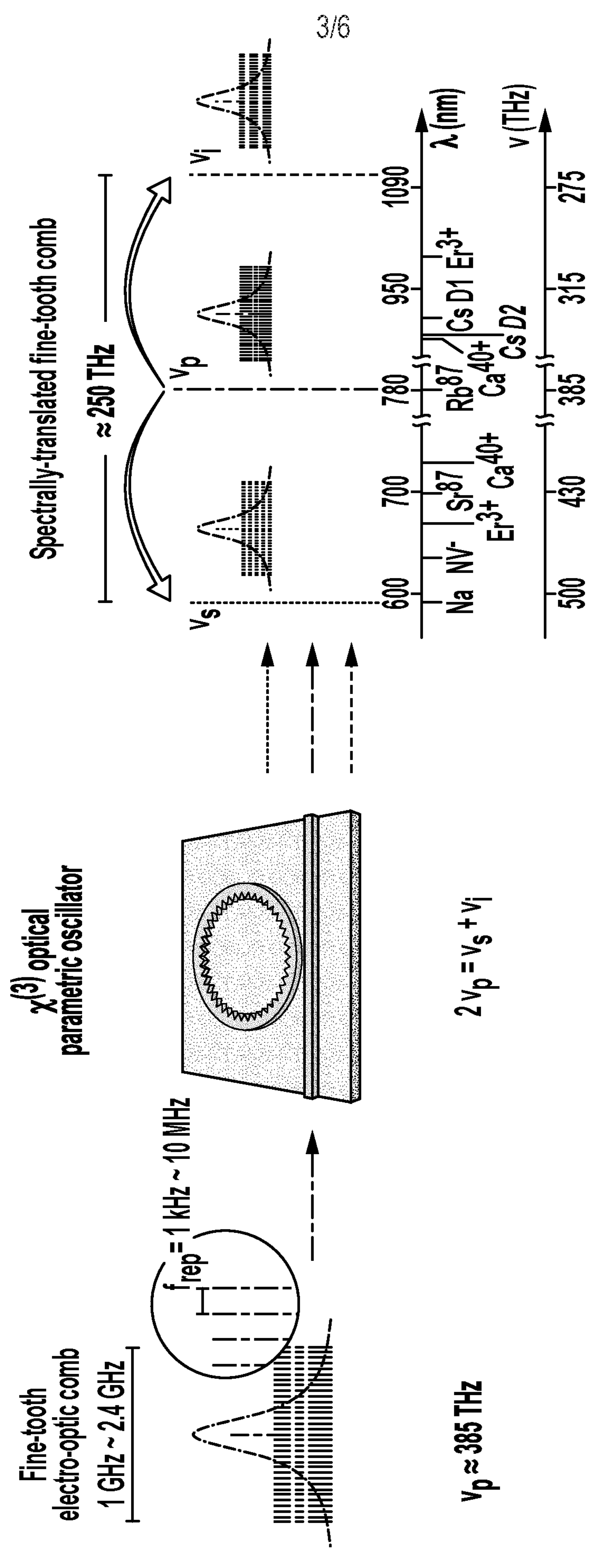

Fine-tooth
electro-optic comb
1 GHz ~ 2.4 GHz
f_{rep} = 1 kHz ~ 10 MHz
$\nu_p \approx$ 385 THz
$\chi^{(3)}$ optical
parametric oscillator
$2\nu_p = \nu_s + \nu_i$
Spectrally-translated fine-tooth comb
≈ 250 THz
ν_s
ν_p
ν_i
600
700
780
950
1090
λ (nm)
Na
NV-
Er^{3+}
Sr^{87}
Ca^{40+}
Rb^{87}
Ca^{40+}
Cs D2
Cs D1
Er^{3+}
500
430
385
315
275
ν (THz)

FIG. 3

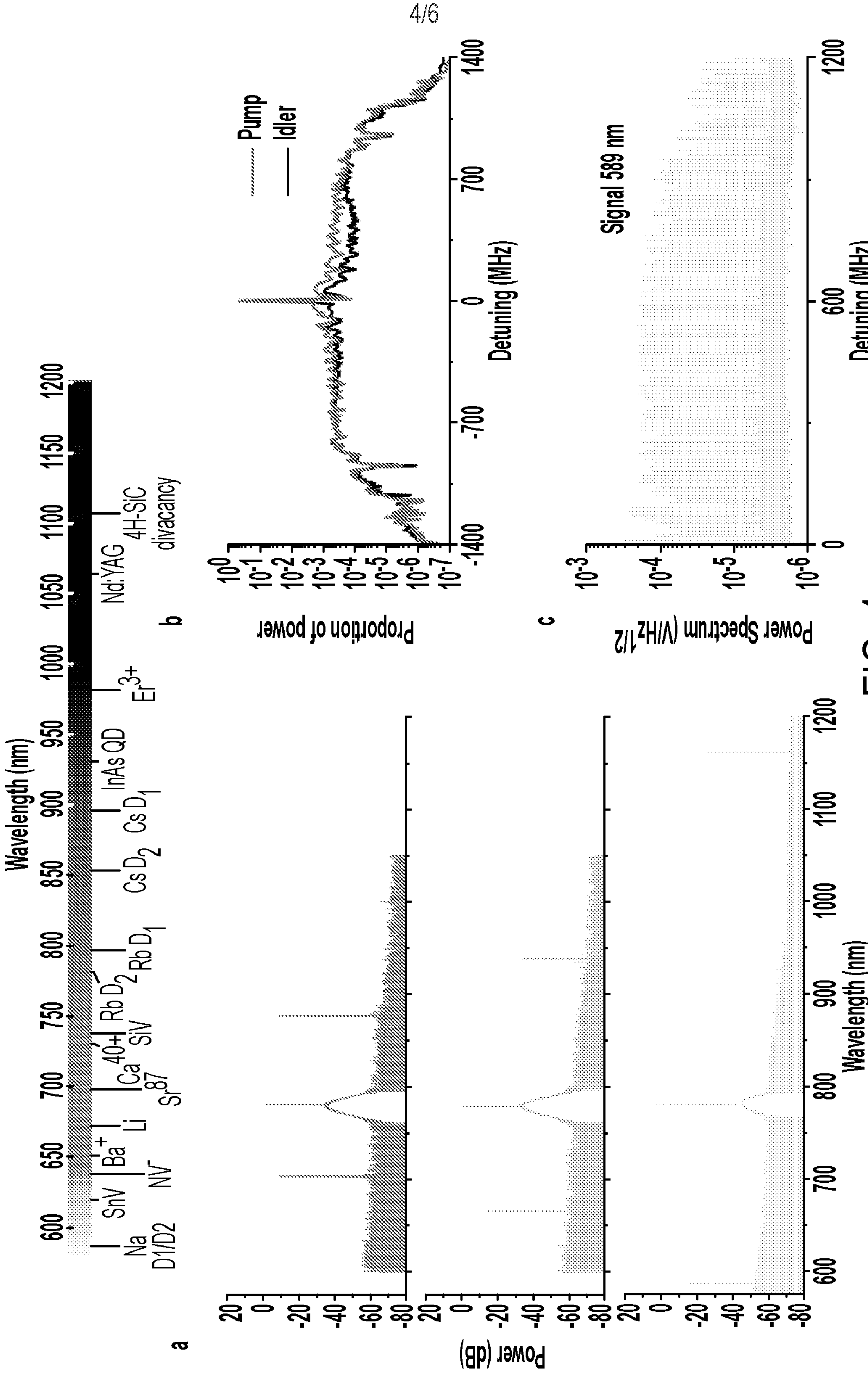
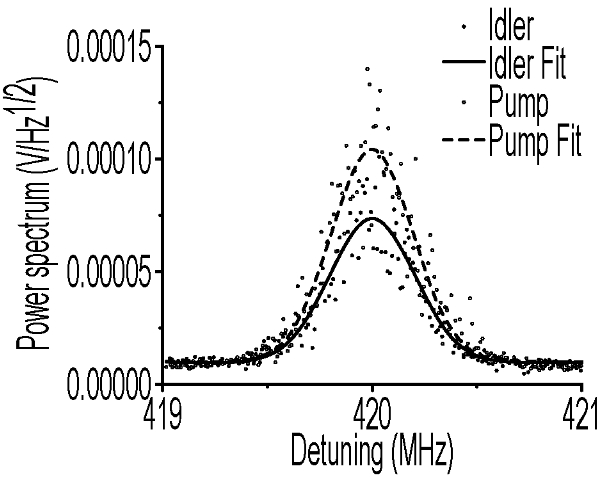

Wavelength (nm)
Na D1/D2
SnV
NV⁻
Ba⁺
Li
Sr⁸⁷
Ca⁴⁰⁺
SiV
Rb D2
Rb D1
Cs D2
Cs D1
InAs QD
Er³⁺
Nd:YAG
4H-SiC divacancy
a
Power (dB)
Wavelength (nm)
b
Proportion of power
Pump
Idler
Detuning (MHz)
c
Power Spectrum (V/Hz^1/2
Signal 589 nm
Detuning (MHz)

FIG. 4

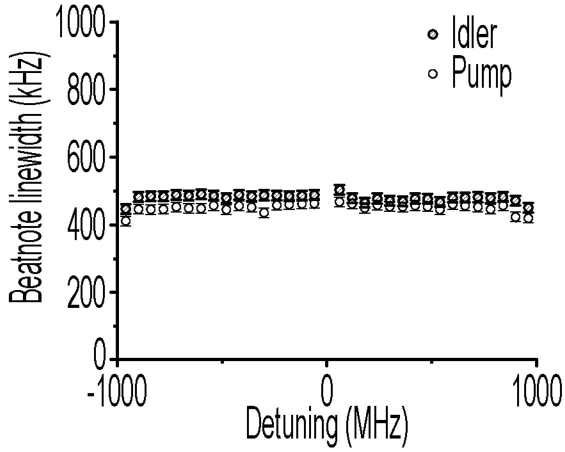
	Pump Before Amp.	Pump After Amp.	Pump After Chip	Idler
Neg. Order	0.112(1)	0.107(7)	0.109(5)	0.077(3)
Carrier	0.789(2)	0.790(5)	0.805(4)	0.882(3)
Pos. Order	0.099(1)	0.103(9)	0.086(7)	0.041(1)

FIG. 5



Idler
Idler Fit
Pump
Pump Fit
Power spectrum (V/Hz$^{1/2}$)
0.00015
0.00010
0.00005
0.00000
419
420
421
Detuning (MHz)

FIG. 6



Idler
Pump
Beatnote linewidth (kHz)
1000
800
600
400
200
0
-1000
0
1000
Detuning (MHz)

FIG. 7

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2024/041944

A. CLASSIFICATION OF SUBJECT MATTER
INV. G02F1/35 H01S3/00
ADD.

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)
G02F H01S

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 practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	SIMON J HERR ET AL: "Frequency comb up- and down-conversion in a synchronously-driven chi^(2) optical microresonator", ARXIV.ORG, CORNELL UNIVERSITY LIBRARY, 201 OLIN LIBRARY CORNELL UNIVERSITY ITHACA, NY 14853, 30 August 2018 (2018-08-30), XP081267597, the whole document -----	1-4,6-20

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[x] Further documents are listed in the continuation of Box C.

[x] See patent family annex.

* Special categories of cited documents :

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
21 November 2024	10/12/2024

Name and mailing address of the ISA/	Authorized officer
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INTERNATIONAL SEARCH REPORT

International application No

PCT/US2024/041944

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	BLACK JENNIFER A ET AL: "Broadband Nonlinear Wavelength Conversion with Integrated Microresonators", 2022 JOINT CONFERENCE OF THE EUROPEAN FREQUENCY AND TIME FORUM AND IEEE INTERNATIONAL FREQUENCY CONTROL SYMPOSIUM (EFTF/IFCS), IEEE, 24 April 2022 (2022-04-24), pages 1-4, XP034165771, DOI: 10.1109/EFTF/IFCS54560.2022.9850772 [retrieved on 2022-08-15] the whole document -----	1,3-19
X	US 2021/080805 A1 (SRINIVASAN KARTIK ARVIND [US] ET AL) 18 March 2021 (2021-03-18) abstract; figure 16 paragraphs [0045], [0051], [0059] -----	1,17,20
X	Albert Schliesser ET AL: "Mid-infrared frequency combs", Nature Photonics, 1 July 2012 (2012-07-01), pages 440-449, XP055320174, London DOI: 10.1038/nphoton.2012.142 Retrieved from the Internet: URL:https://arxiv.org/ftp/arxiv/papers/1205/1205.3395.pdf [retrieved on 2016-11-16] the whole document -----	1,17,20

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2024/041944

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2021080805 A1	18-03-2021	NONE	