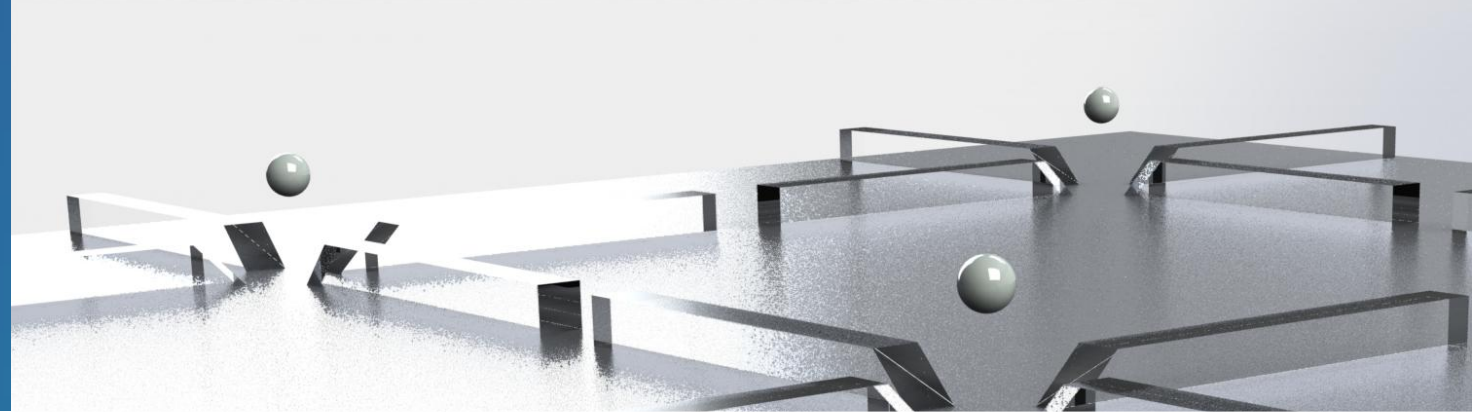
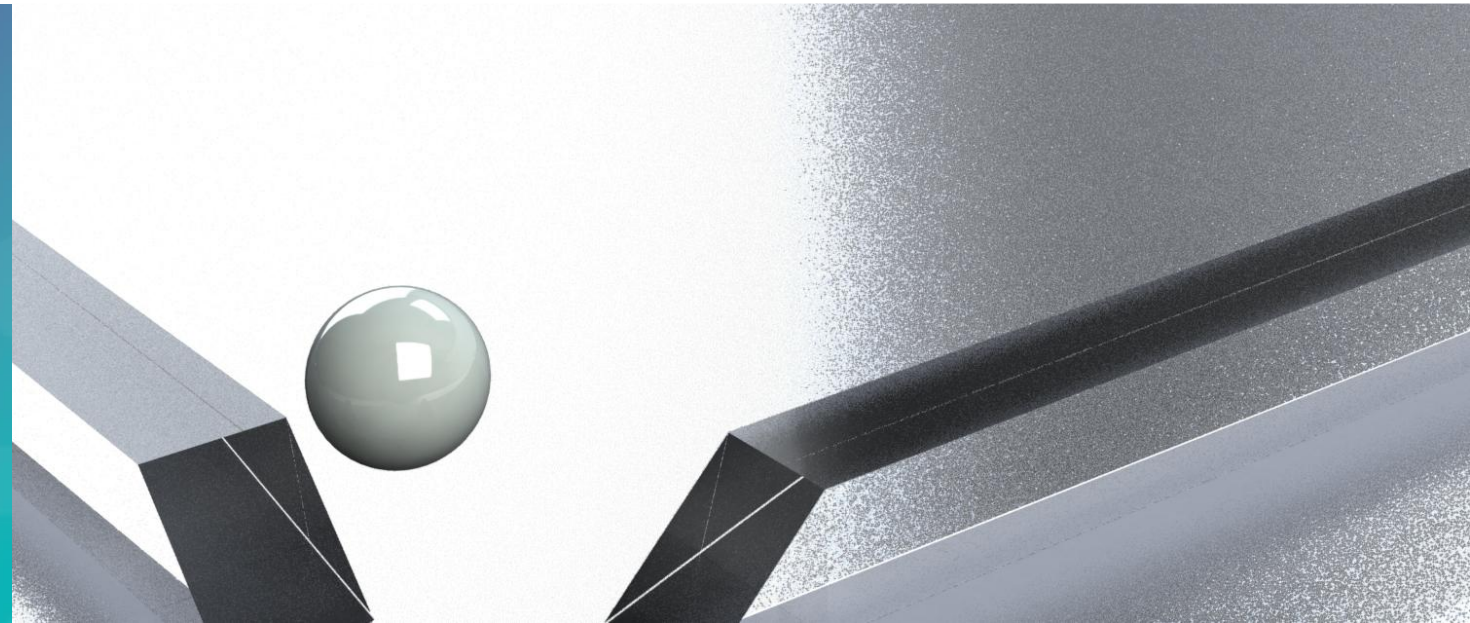
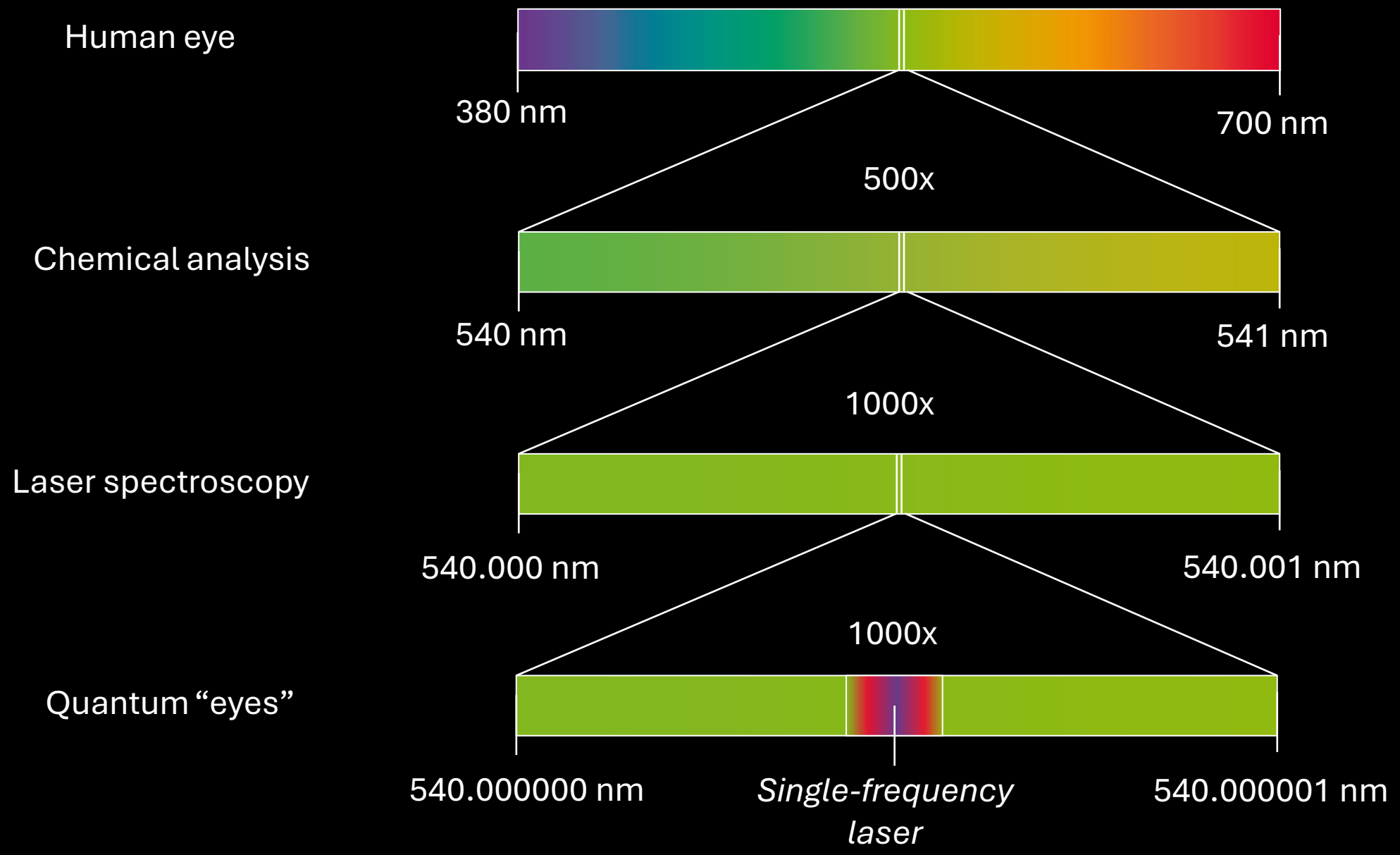


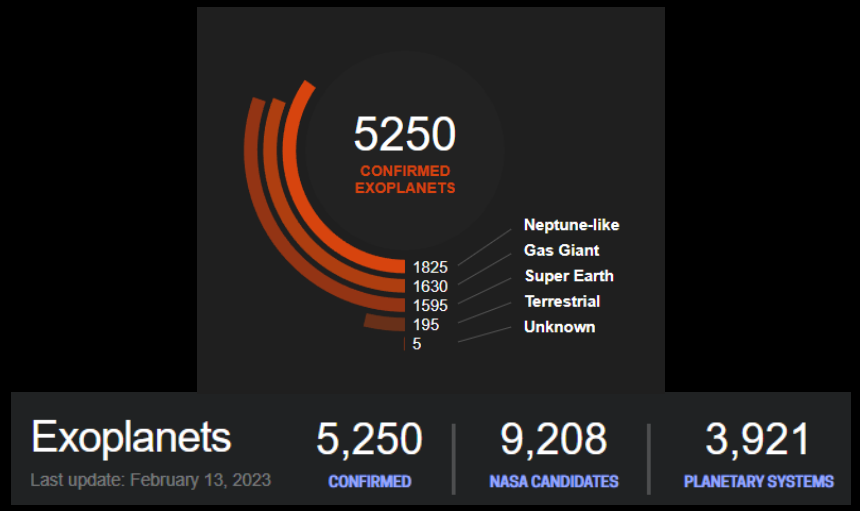
Integrated Diamond Lasers for Quantum Applications: Compact, Ultra-Stable, and Cost-Effective

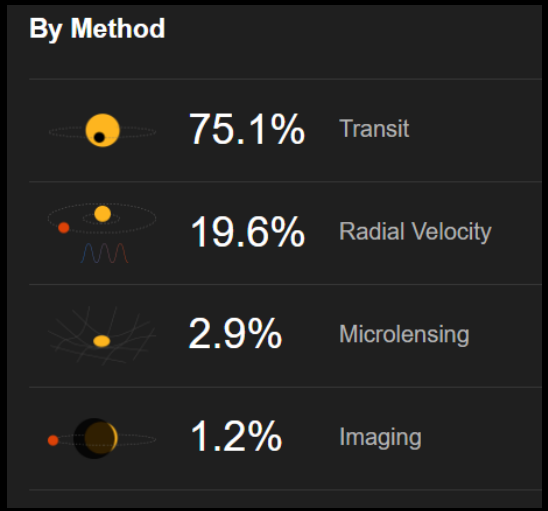
Eduardo Granados, CERN

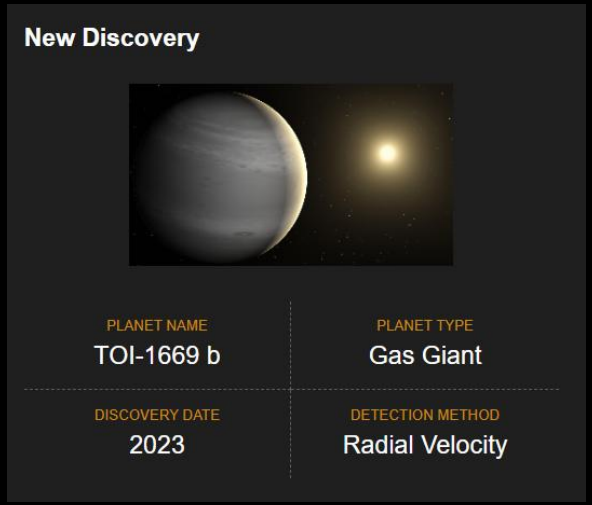



Human eye
380 nm
700 nm
500x
Chemical analysis
540 nm
541 nm
1000x
Laser spectroscopy
540.000 nm
540.001 nm
1000x
Quantum “eyes”
540.000000 nm
Single-frequency laser
540.000001 nm

Exoplanet hunting

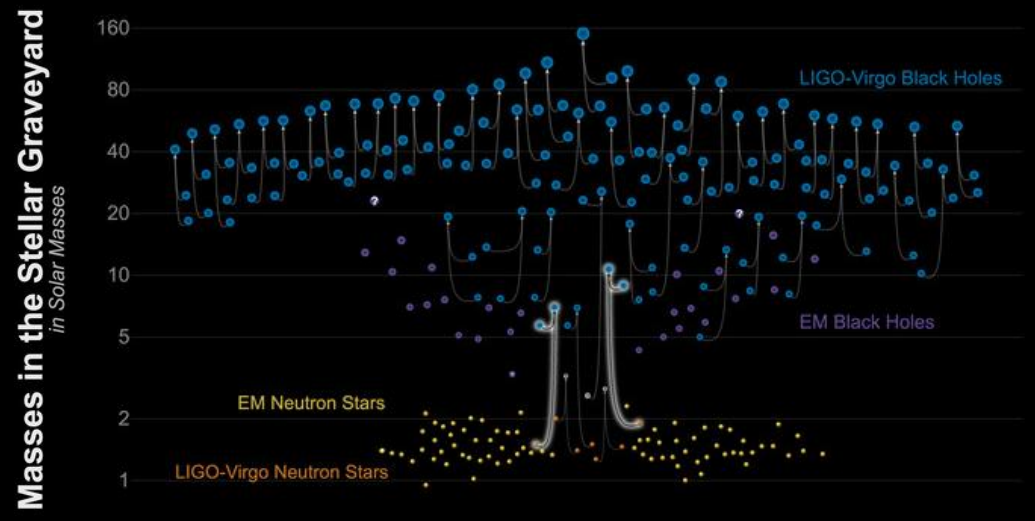






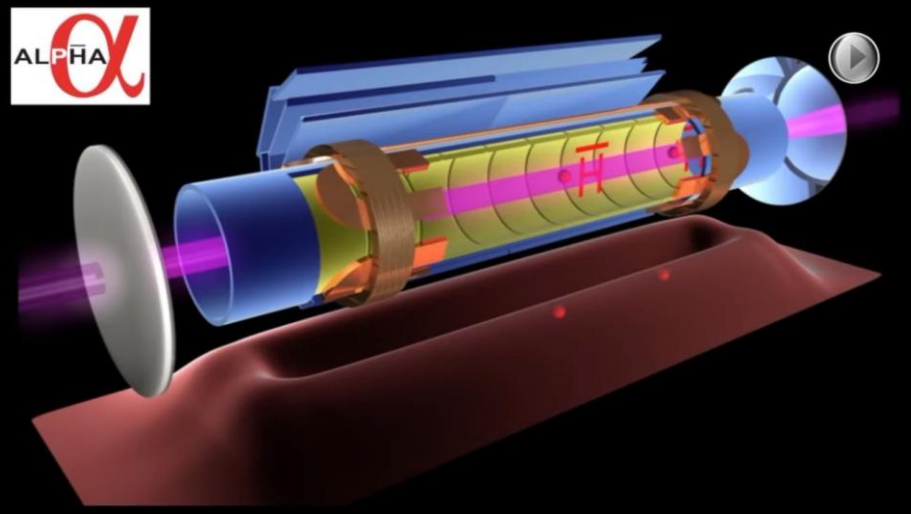
Source: NASA

Gravitational wave surfing



Source: LIGO - Caltech/MIT

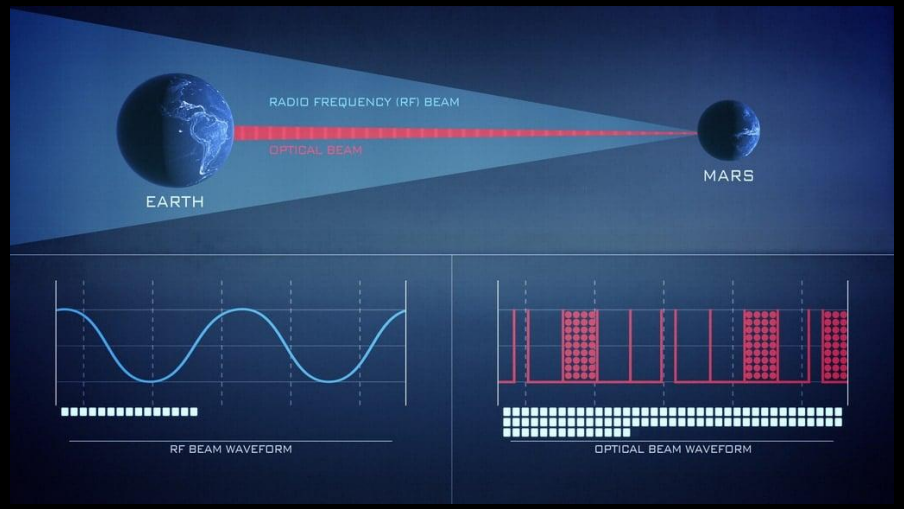
Anti-matter



Source: CERN

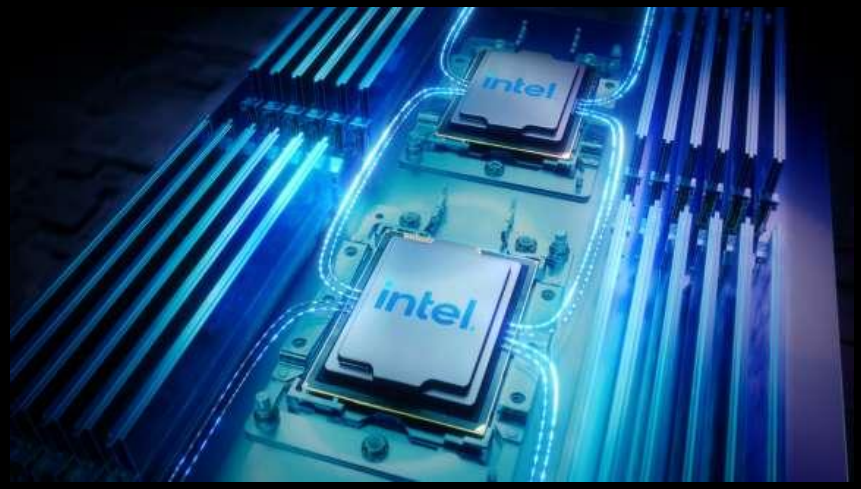
Data links

Source: SpaceNews



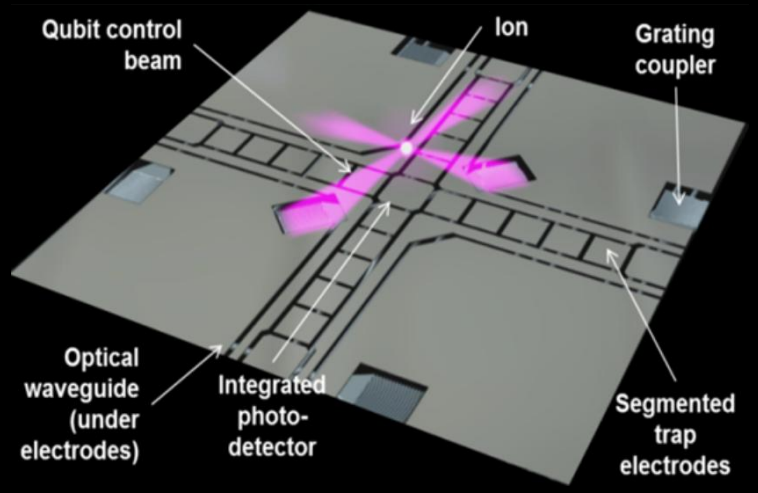
Source: NASA

Photonic Integrated Circuits

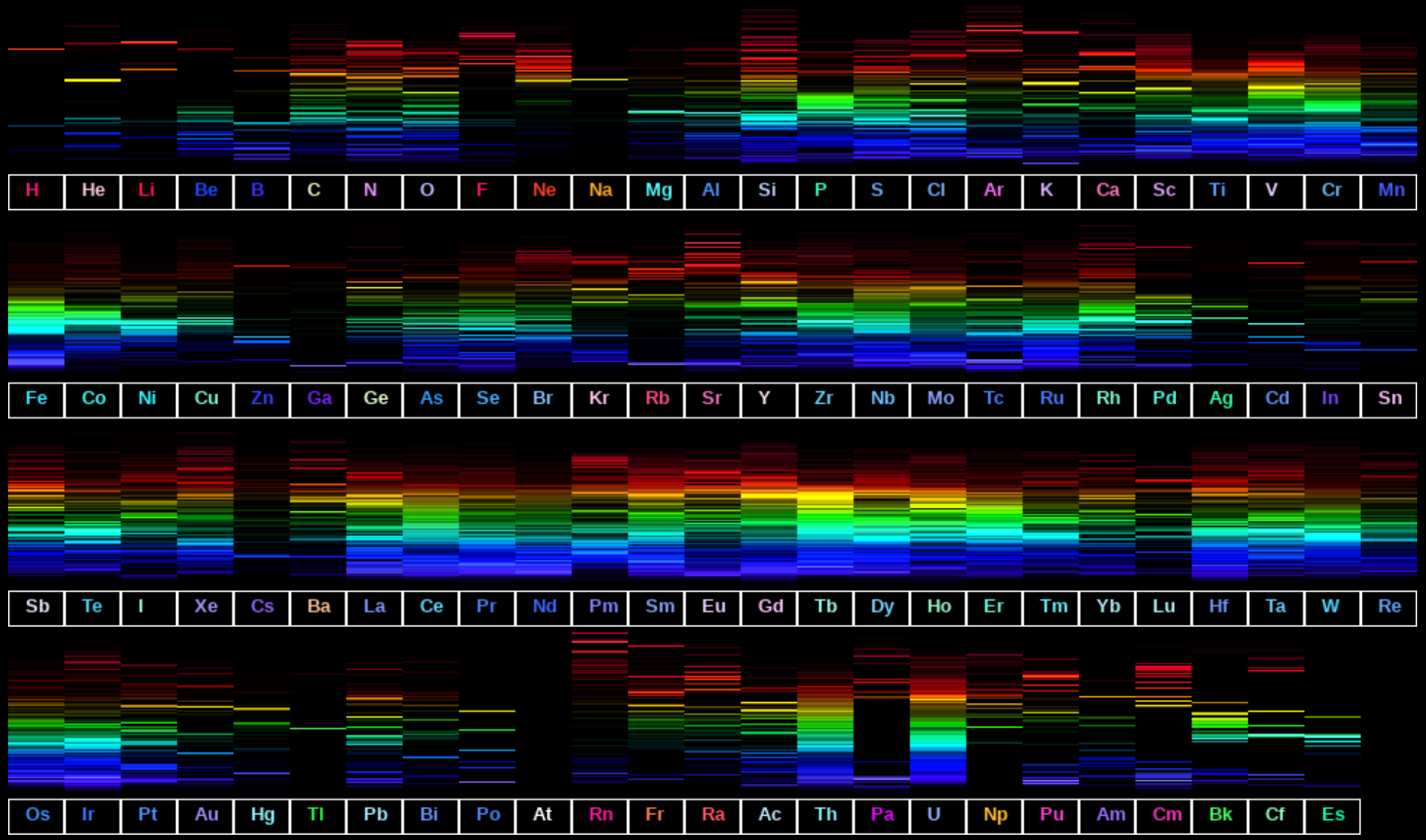


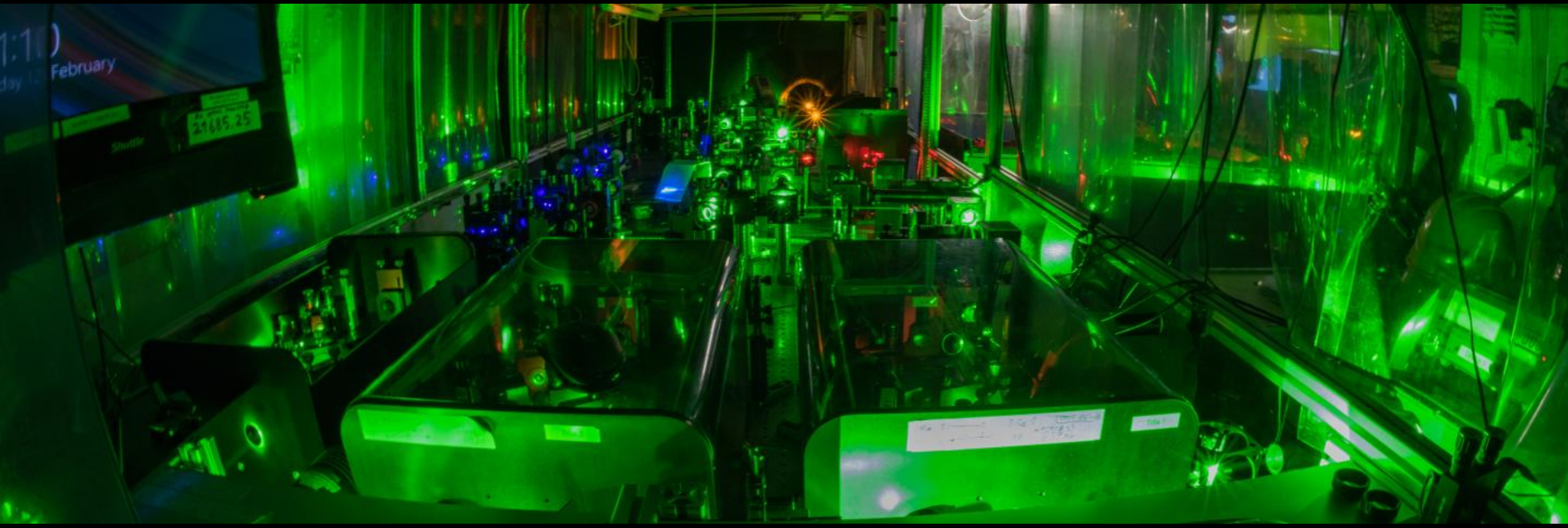
Source: Intel

Quantum computing



Source: MIT LL


H He Li Be B C N O F Ne Na Mg Al Si P S Cl Ar K Ca Sc Ti V Cr Mn
Fe Co Ni Cu Zn Ga Ge As Se Br Kr Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn
Sb Te I Xe Cs Ba La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu Hf Ta W Re
Os Ir Pt Au Hg Tl Pb Bi Po At Rn Fr Ra Ac Th Pa U Np Pu Am Cm Bk Cf Es



Can we produce light in the visible part of the spectrum in a different way?

nature photonics

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Published: April 2010

Yellow lasers

A little diamond goes a long way

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Carbon optimism

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TECHNOLOGY

Diamonds Lose Mass in Sunlight

Carbon atoms set free by ultraviolet light.

July 15, 2011

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Science > Energy

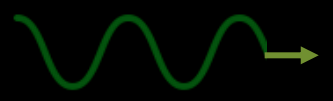
New Laser Burns Hotter Than the Sun And Creates Mini-Stars in the Lab

Paired with the Linac Coherent Light Source, the new laser can create planet cores, repair airplane parts, and push the frontiers of particle science.

Why not using diamond?

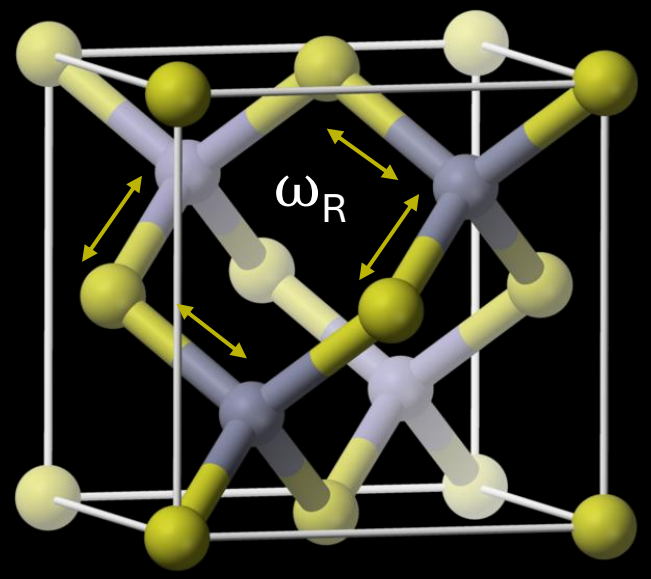
The (stimulated) Raman effect

Incoming photon



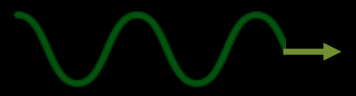
ω_p

crystal



Possible outcomes

transmission



ω_p

Stokes

$\omega_S = \omega_p - \omega_R$

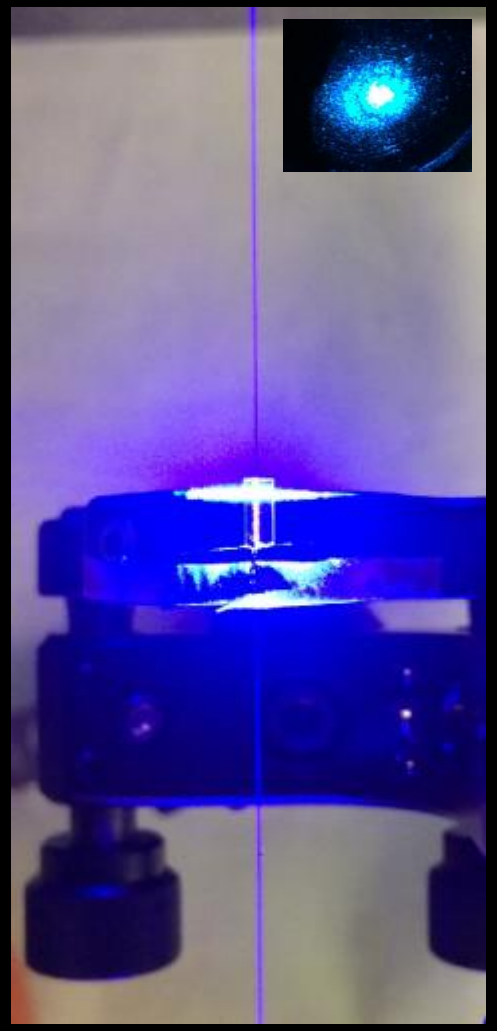
anti-Stokes

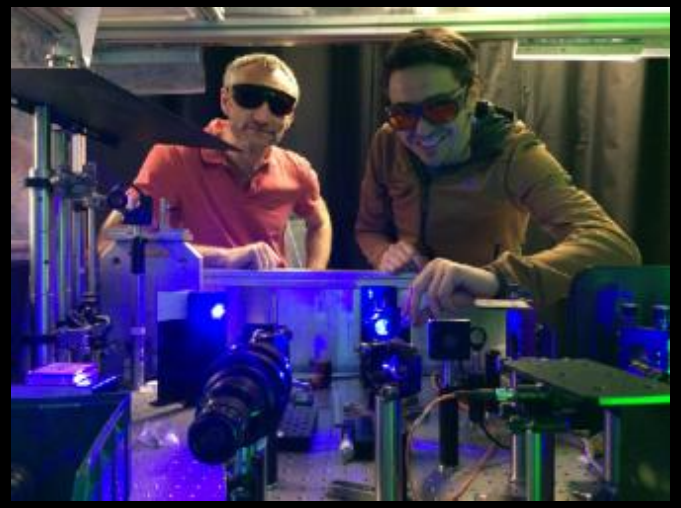
$\omega_{aS} = \omega_p + \omega_R$

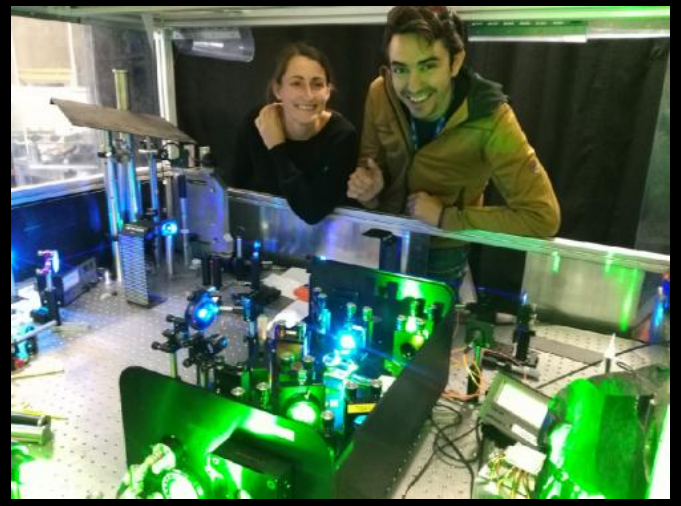
- The Raman shift (ω_R) depends on the crystal
- The Raman gain depends on the crystal
- The spectral range also depends on the crystal

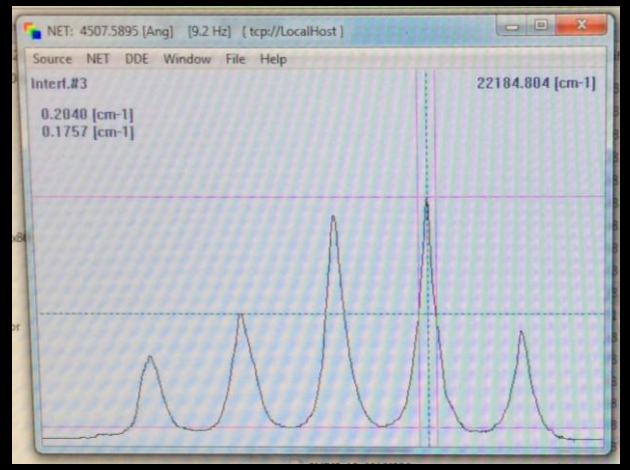
The "*best one*" overall is:
DIAMOND

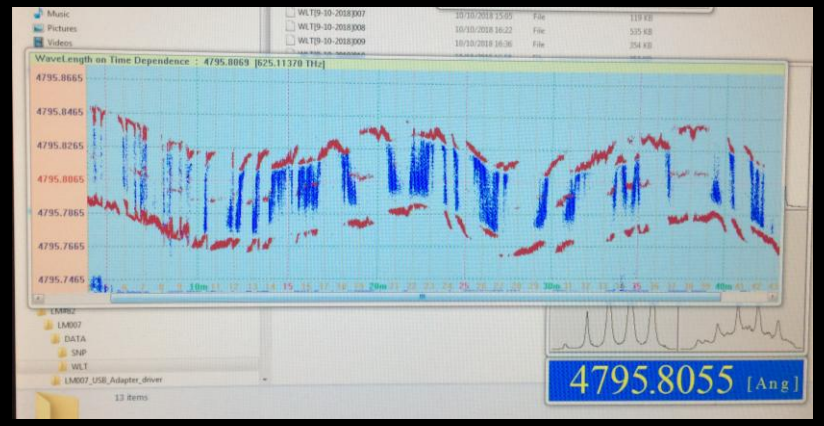
October 2018





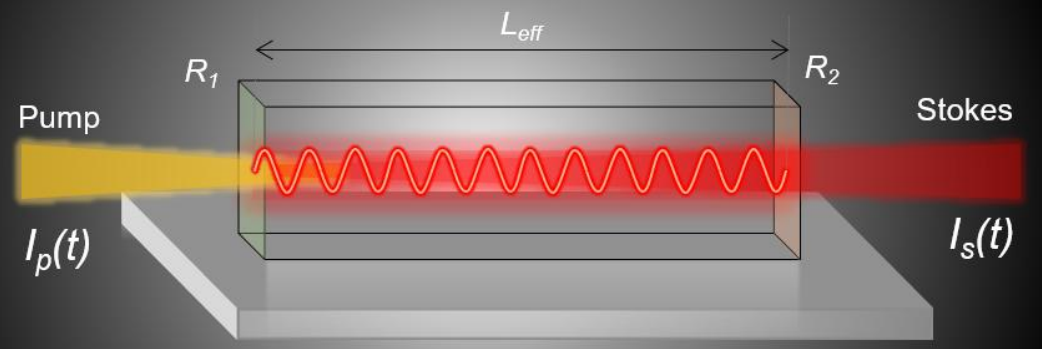






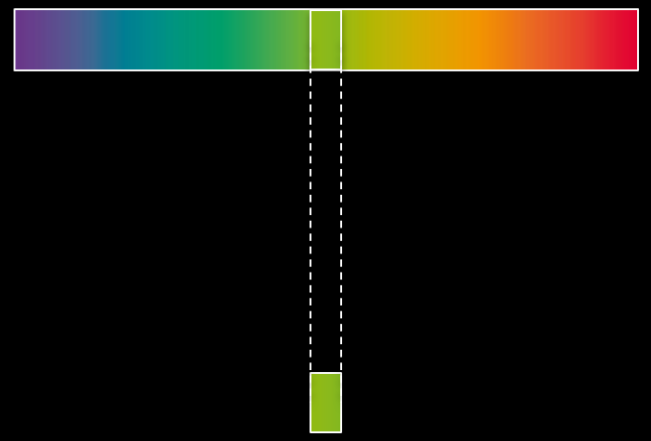
We produced for the 1st time tunable single frequency light using Raman lasers!

The device is incredibly simple!

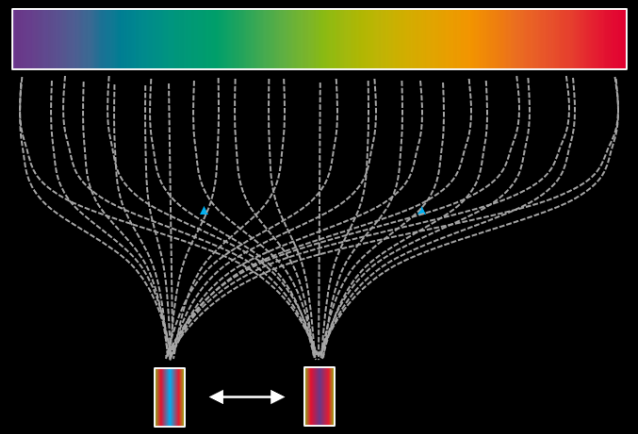


Works at any wavelength from the UV to THz!
-> **NEW** device for integrated photonics toolbox

Filtering



"Funneling"



Increased the brightness by 50x
Reduced the bandwidth by 100x

OPTICA

Spectral synthesis of multimode lasers to the Fourier limit in integrated Fabry–Perot diamond resonators

Eduardo Granados,[1,*] Camilo Granados,[2] Rizwan Ahmed,[1] Katerina Chrysalidis,[1] Valentin N. Fedosseev,[1] Bruce A. Marsh,[1] Shane G. Wilkins,[1] Richard P. Mildren,[3] and David J. Spence[3]

[1]CERN, 1217 Geneva, Switzerland
[2]Max-Born-Institut für nichtlineare Optik und Kurzzeitspektroskopie, 12489, Berlin, Germany
[3]MQ Photonics Research Centre, Macquarie University, Sydney, NSW 2109, Australia
*Corresponding author: eduardo.granados@cern.ch

Received 1 November 2021; revised 18 February 2022; accepted 22 February 2022; published 17 March 2022

Fourier-limited nanosecond pulses featuring narrow spectral bandwidths are required for applications in spectroscopy, sensing, and quantum optics. Here, we demonstrate a direct and simple route for the generation of single-frequency light relying on phonon-resonant Raman interactions within a monolithic diamond resonator. The technique enables the production of nearly Fourier-limited nanosecond optical pulses (15 ns), with an overall spectral bandwidth of down to 180 MHz, which is nearly two orders of magnitude narrower than the pump laser linewidth used (12 GHz). The power conversion efficiency was 47%, yielding a power spectral brightness enhancement of >50× compared to the pump. Our results pave the way to the integration of pulsed widely tunable, power scalable, narrow linewidth light sources into integrated photonic platforms. Furthermore, the device does not need elaborate mechanical feedback loops for cavity length or frequency stabilization, or any additional optical components. © 2022 Optica Publishing Group under the terms of the Optica Open Access Publishing Agreement

https://doi.org/10.1364/OPTICA.447380

1. INTRODUCTION

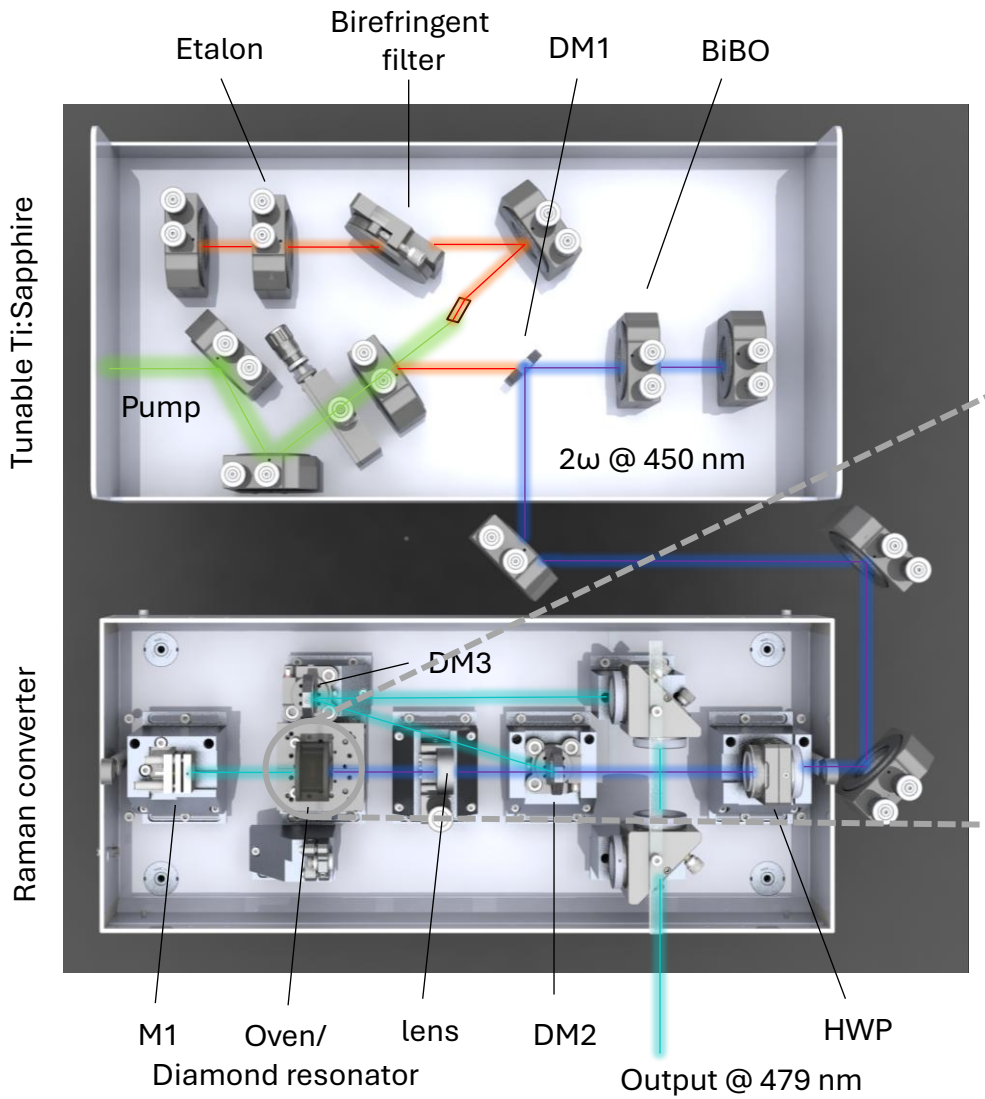
The frequency synthesis and spectral content of lasers have been topics of investigation since the invention of the laser. Narrow linewidth and single longitudinal mode (SLM) lasers have become the prime tools for modern applications where high stability and precision are required. These include the development of atomic clocks [1], atomic matter and antimatter cooling [2], high-resolution spectroscopy [3], physics beyond the standard model [4], or lidar [5], to name a few. Applications on laser spectroscopy of radioactive elements [6–8] and the increasing interest for the study of chemical elements where no atomic information is known [9], is just another example where SLM laser sources with MHz-class linewidths are of imperative importance.

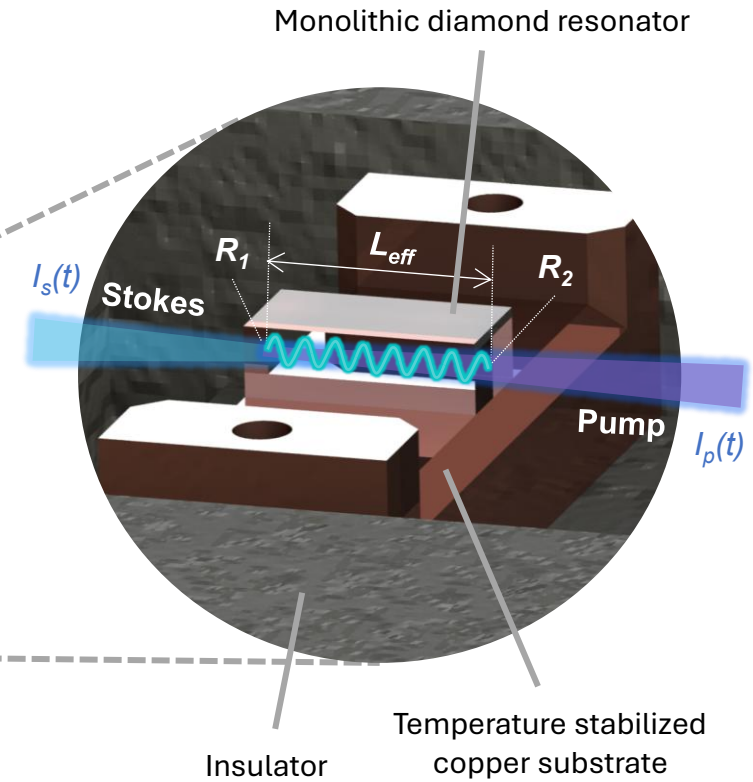
The advent of quantum-technology-based sensing and photonic sources has increased the interest in producing and integrating pulsed narrow linewidth lasers [10]. Here, the main challenge is in the complexity of producing widely tunable, high-performance narrowband lasers (in the kHz to hundreds of MHz) at a range of wavelengths that are used to cool, trap, and manipulate ions [11]. Eventually, photonic integrated circuits (PICs) are expected to provide the scalability and simplicity required to enable quantum-technology-based sensing systems and applications, but multiple advances are still needed. Among these, improvements in active materials (e.g., direct gain and laser output in the green-yellow spectral range) and passive materials (low-loss waveguides, especially in the UV blue range) could enable a viable path for wafer-scale integration [12].

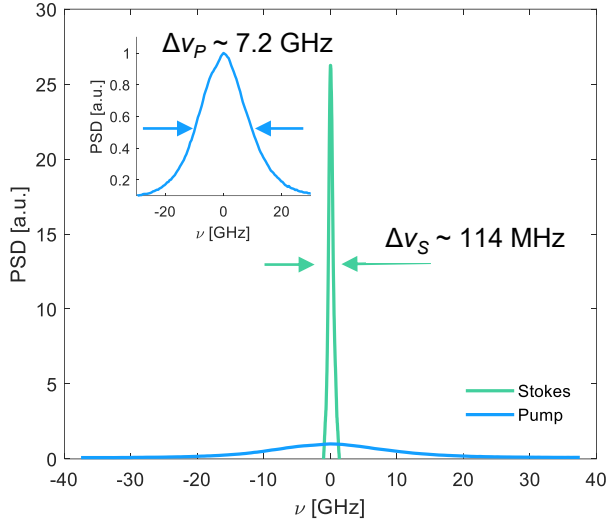
While many methods to generate a stable phase-coherent train of ultrafast laser pulses are available now [13–15], these methods only provide limited access to the generation of stable coherent nanosecond pulses. By using injection-locking in Ti:sapphire [16], VCSEL [17], and fiber-based [18] lasers or external electro-optic modulation of single-frequency fibers [19], nearly Fourier-limited ns pulses have been achieved with flexible pulse durations, repetition rates, and tunability ranges. However, such schemes are usually associated with significant experimental complexity and cost, typically produce outputs with high noise figures and no pulse-to-pulse temporal coherence, and are usually not integrable on a chip.

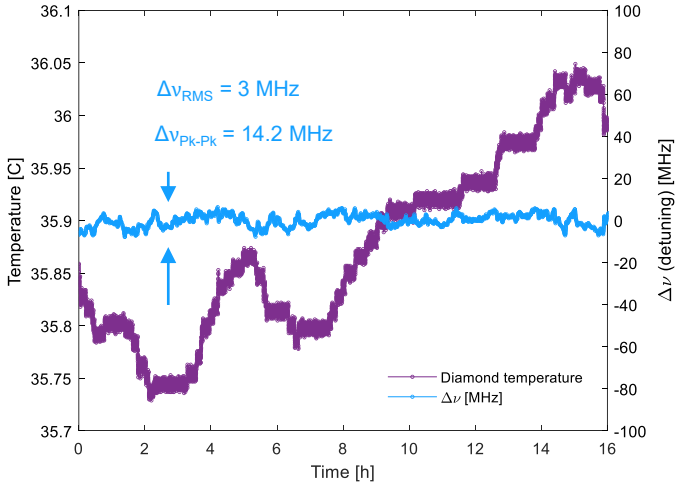
Alternatively, taking advantage of the traditionally superior noise characteristics of passive mode-locking techniques, graphene-based saturable absorbers have been used for mode-locking ns pulses [20–22]. However, these systems produced chirped pulses with linewidths in the few-GHz range, caused mainly by the disadvantageous operation timescales of saturable absorbers, as well as by the low strength of the nonlinear effects reachable through ns pulses with moderate energies. More recently,

MHz-class tuning over 300 – 1200 nm spectral range



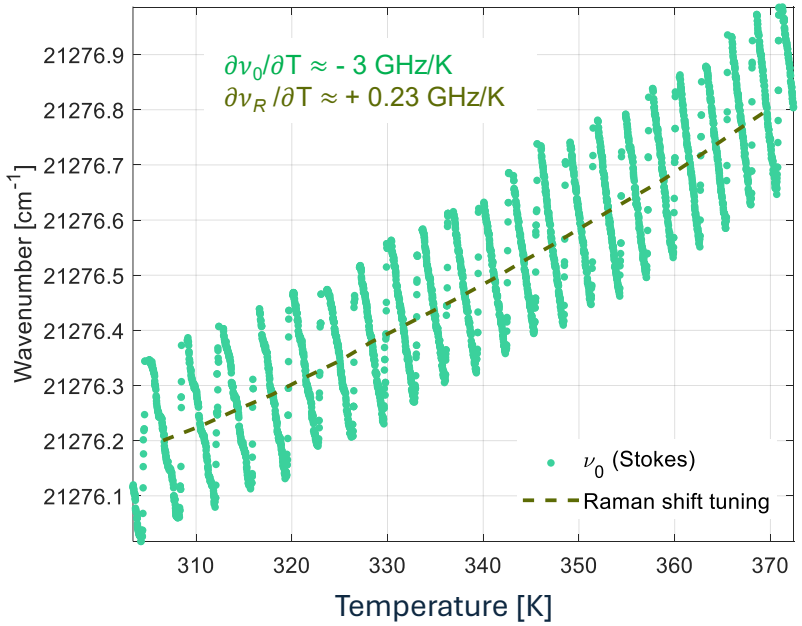


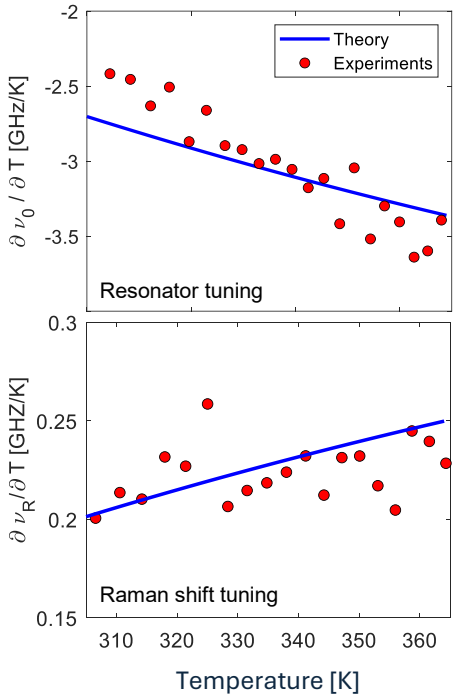




E. Granados, et al, "Tunable spectral squeezers based on monolithically integrated diamond Raman resonators". ***Appl. Phys. Lett.*** 11 April 2022; 120 (15): 151101.

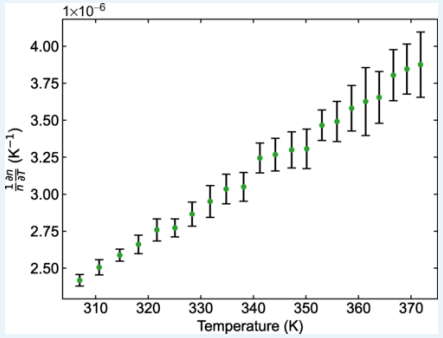
MHz-class tuning over 300 – 1200 nm spectral range

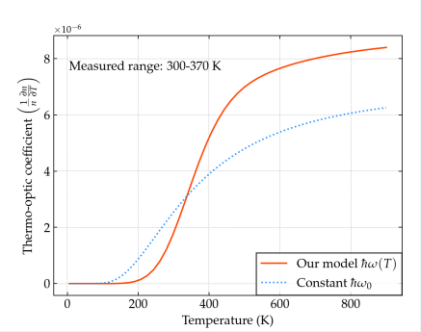




Tuning performance

- Easy to achieve **<20 MHz steps**
- Temperature precision **10 mK** necessary
- **Raman shift tuning** helps to expand the spectral coverage of the laser.
- **Mode-hop free** tuning demonstrated for > 20 GHz without tuning the pump laser.
- Better results expected for **low temperature**





Resonator tuning

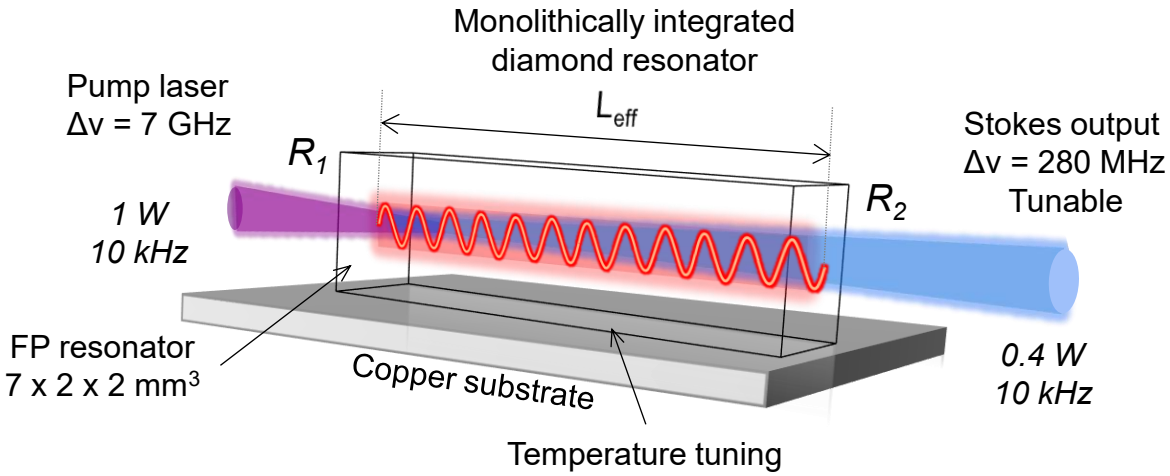
$$\frac{\partial\nu_0}{\partial T} = -\frac{c}{\lambda_S}\frac{(1/n)(\partial n/\partial T)+\alpha}{1-\lambda_S(1/n)(\partial n/\partial\lambda)}$$

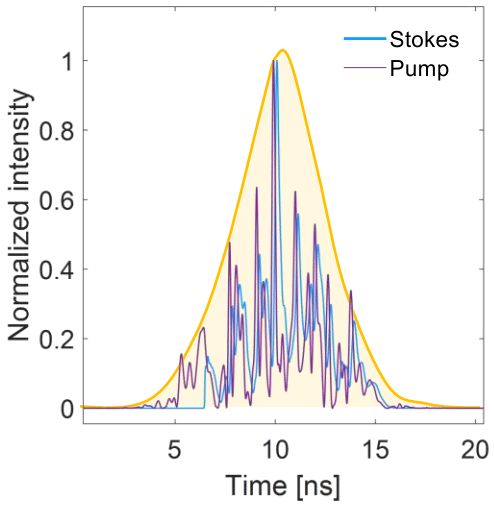
Raman shift tuning

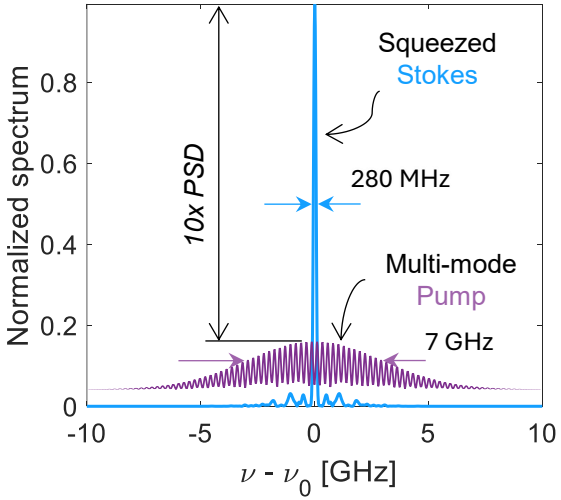
$$\nu_R(T) = -B\left(\frac{2}{e^{\hbar\omega_0/2k_BT}-1}\right)$$

E. Granados, et al, "Tunable spectral squeezers based on monolithically integrated diamond Raman resonators". ***Appl. Phys. Lett.*** 11 April 2022; 120 (15): 151101.
G. Stoikos and E. Granados, "Influence of phonon harmonicity on spectrally pure resonant Stokes fields" ***Phys. Rev. A*** 106, 023504 (2022)

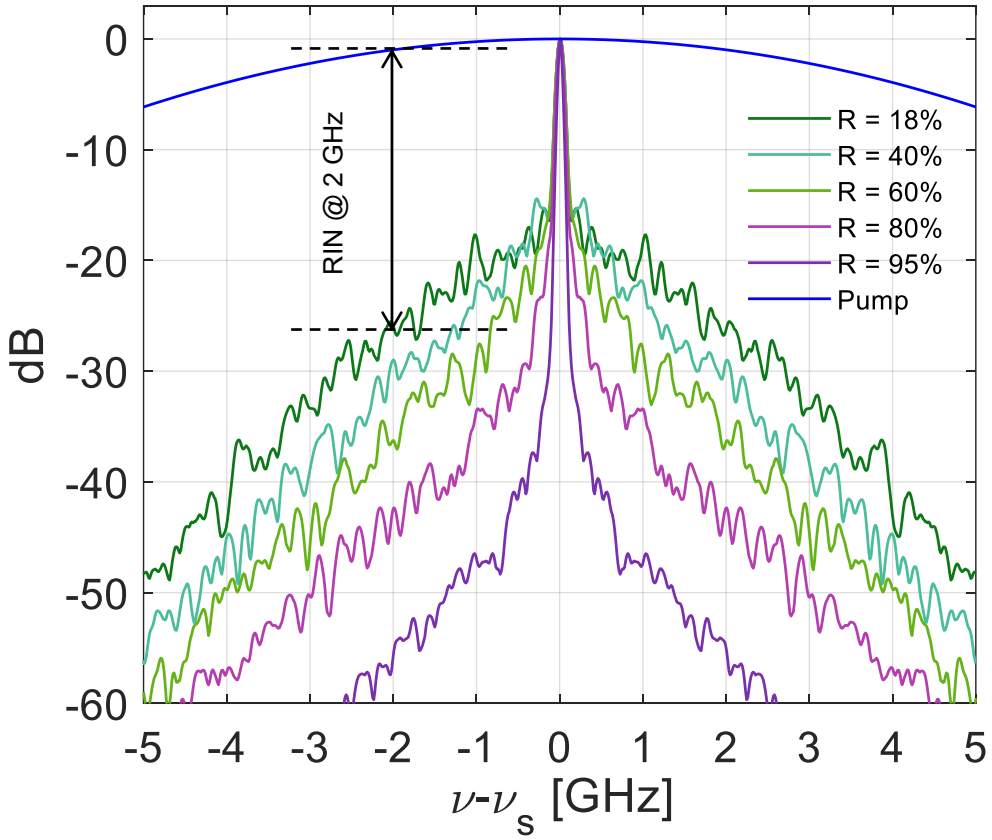
Stokes spectral purity and residual side-modes



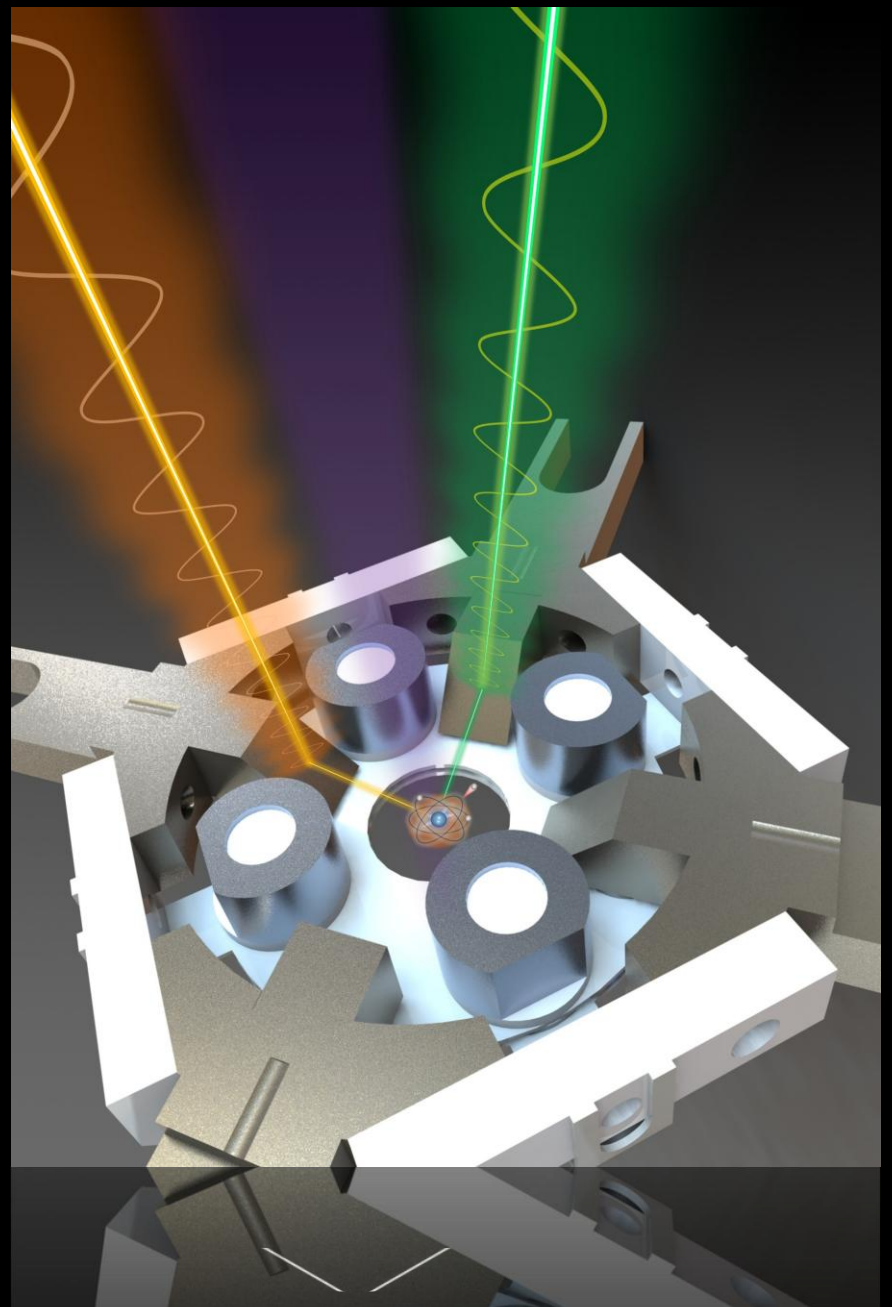




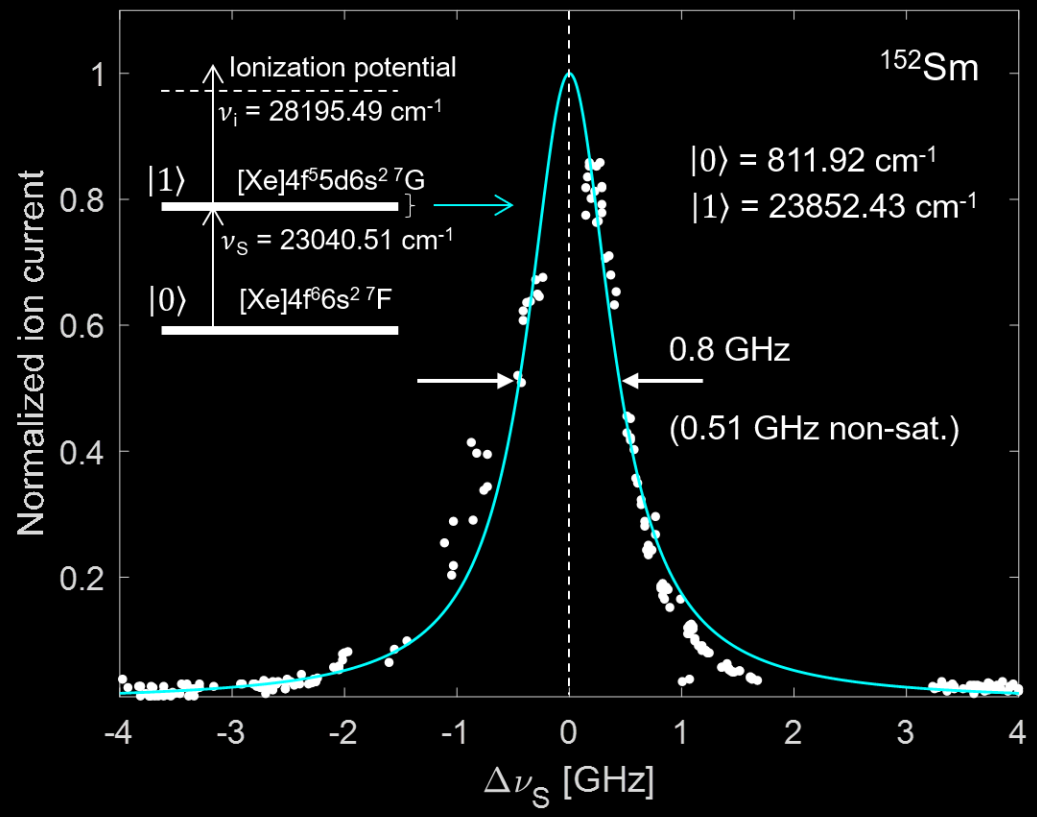
Residual side-modes are critical for spectroscopy (and other) applications



Laser & Photonics Reviews, 18:2470018 (2024) https://doi.org/10.1002/lpor.202470018



First demonstration of a Raman laser accessing hyperfine structure of an atom



Laser & Photonics Reviews, 18:2470018 (2024) https://doi.org/10.1002/lpor.202470018

In-Source High-Resolution Spectroscopy Using an Integrated Tunable Raman Laser

Eduardo Granados, Georgios Stoikos, Cyril Bernerd, Katerina Chrysalidis, Daniel T. Echarri, Valentin N. Fedosseev, Reinhard Heinke, and Bruce A. Marsh*

Dedicated to the memory of Steve Edstrom

Tunable single-frequency lasers are the most prominent tool for high-resolution spectroscopy, allowing for the study and exploitation of the electronic structure of atoms. A significant milestone relies on the demonstration of integrated laser technology for performing such a task. The device presented here is composed of a compact Fabry–Perot monolithic resonator capable of producing tunable and Fourier-limited nanosecond pulses with a MHz-class frequency stability without active cavity stabilization elements. It also has the remarkable capability of exploiting the Raman effect to funnel efficiently the broad spectrum of an input laser to a spectrally-bright Stokes pulse at hard-to-access wavelength ranges. The targeted atom for the demonstrations is ^{152}Sm, released as an atomic vapor in a hot cavity environment. Here, the Stokes field is tuned to a wavelength of 433.9 nm, while a crossed-beams spectroscopy setup is used to minimize the Doppler broadened spectral features of the atoms. With this work, the suitability of integrated diamond Raman lasers as a high-resolution in-source spectroscopy tool is demonstrated, enabling many applications in atomic and nuclear physics. The integrated form-factor and inherent simplicity makes such a laser an interesting prospect for quantum-technology based sensing systems and related applications.

1. Introduction

Deep knowledge of the forces and interactions inside nuclei is the basis for understanding and controlling atomic processes in a wide range of application areas, including atomic clocks,[1,2] quantum computing,[3,4] or nuclear spectroscopy.[5] A gateway to access this information is through the interplay between the electronic and nuclear structure of atoms that is, hyperfine interactions. These interactions are minuscule compared to the dominating thermal and electromagnetic effects occurring in atoms, fuelling the need for high precision and Doppler-free techniques of spectroscopic measurement. Hyperfine spectroscopy reveals highly valuable information related to nuclear properties and atomic structures, including nuclear shape, size and the individual multipole structure of isotopes and isomers all across the chart of nuclides.[6]

The hyperfine states of trapped ions are commonly used for storing qubits in ion-trap quantum computing, thanks to their extended excited state lifetimes.[7] Pairs of laser pulses are used here to drive the transition by having their frequency difference equal to the specific transition's frequency. In general, kHz to MHz linewidth lasers are the necessary tool to cool, selectively excite and ionize atomic species.[2] Integrating such laser sources on a chip is poised to provide the scalability necessary for quantum technology-based sensing systems and applications,[8] but advances are still required in miniature lasers with output in the ultraviolet (UV) and visible spectral range as well as low-loss passive devices such as couplers and waveguides.[4,9] Notably, a substantial portion of the spectrum ranging from the UV to the near-infrared (IR) is only recently becoming accessible using state-of-the-art integrated photonic devices.[10,11]

The production itself of pure ion beams also profits from efficient and tunable narrow linewidth laser sources. Here, Resonance Ionization Spectroscopy is a common technique that enables element-selective ionization by using a series of tunable laser sources matched to the appropriate transitions of an ionization scheme. The selectivity is achieved by consecutive resonant electron excitations, eventually leading above the ionization potential. Once the ions are produced, they can be trapped and manipulated by employing electromagnetic fields. The laser sources used here, besides being energy-matched to the transition (normally in the UV-visible spectral range), are also matched in linewidth to the experimental conditions of the laser-atom interaction for maximum ionization efficiency and must be continuously tunable across the transition for spectroscopy

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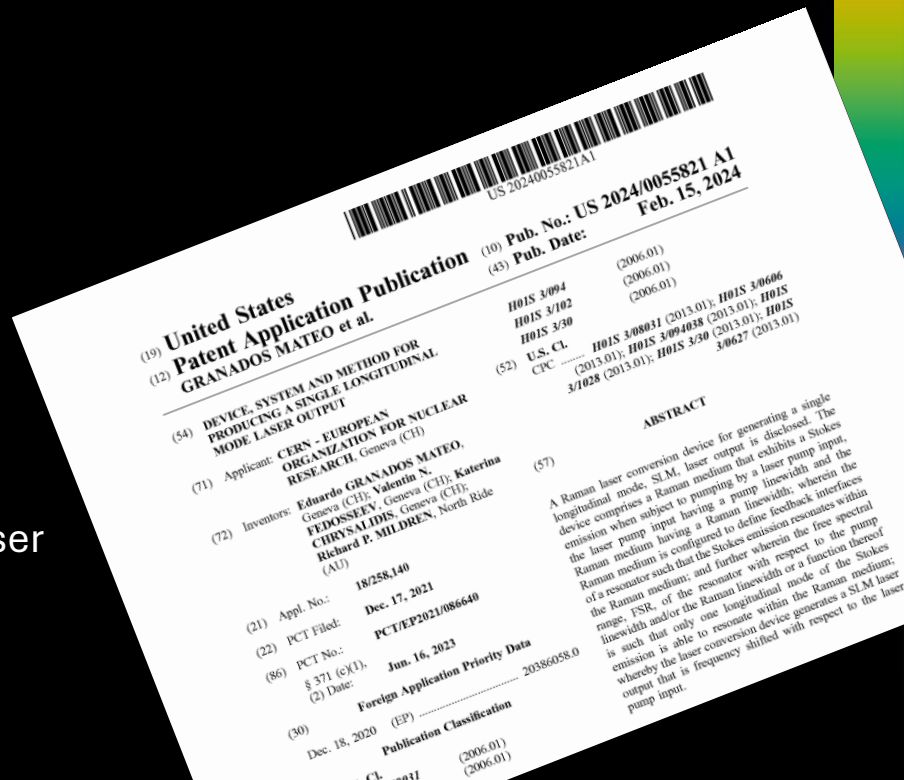
DOI: 10.1002/lpor.202300564

October 2018

8th Oct 2018	1st contact CERN KT
6th Nov 2018	CERN KT Fund drafted
7th Dec 2018	KT project presented: “Singular Light”
11th Jan 2019	KT Funds confirmed: 117,500 CHF
31st Jan 2019	Technology description sent to KT
Jun-Jul 2019	2 students start working on “Singular Light” funded by KT
14th Feb 2019	IP agreement with Macquarie University signed
4th Mar 2020	First draft of patent completed
12th Oct 2020	European patent office - disclosure submitted
17th Dec 2021	PCT patent application was filed after patent search
Jun 2022	Agreement CERN – Enigmedia to test the tech
7th Feb 2023	Follow up from the European patent office
1st Dec 2023	First ion manipulation using an integrated Raman laser
15th Feb 2024	US Patent
25th Aug 2025	Prototypes delivered to startups



(19) United States
(12) Patent Application Publication
GRANADOS MATEO et al.

(10) Pub. No.: US 2024/0055821 A1
(43) Pub. Date: Feb. 15, 2024

(54) DEVICE, SYSTEM AND METHOD FOR PRODUCING A SINGLE LONGITUDINAL MODE LASER OUTPUT

(71) Applicant: CERN - EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH, Geneva (CH)

(72) Inventors: Eduardo GRANADOS MATEO, Geneva (CH); Valentin N. FEDOSSEEV, Geneva (CH); Katerina CHRYSALIDIS, Geneva (CH); Richard P. MILDREN, North Ride (AU)

(21) Appl. No.: 18/258,140
(22) PCT Filed: Dec. 17, 2021
(86) PCT No.: PCT/EP2021/086640
§ 371 (c)(1), (2) Date: Jun. 16, 2023
(30) Foreign Application Priority Data
Dec. 18, 2020 (EP) 20386058.0
Publication Classification

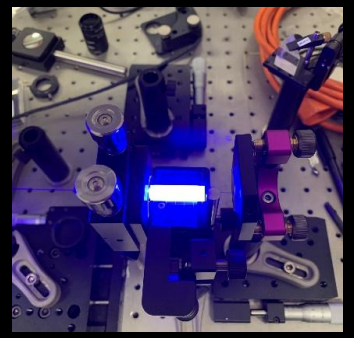
H01S 3/094 (2006.01)
H01S 3/102 (2006.01)
H01S 3/30 (2006.01)
(52) U.S. Cl. CPC H01S 3/08031 (2013.01); H01S 3/0606 (2013.01); H01S 3/094038 (2013.01); H01S 3/30 (2013.01); H01S 3/1028 (2013.01); H01S 3/0627 (2013.01)

ABSTRACT

(57) A Raman laser conversion device for generating a single longitudinal mode, SLM, laser output is disclosed. The device comprises a Raman medium that exhibits a Stokes emission when subject to pumping by a laser pump input, the laser pump input having a Raman linewidth and the Raman medium is configured to define feedback interfaces of a resonator such that the Stokes emission resonates within the Raman medium; and further wherein the free spectral range, FSR, of the resonator with respect to the pump linewidth and/or the Raman linewidth or a function thereof is such that only one longitudinal mode of the Stokes emission is able to resonate within the Raman medium, whereby the laser conversion device generates a SLM laser output that is frequency shifted with respect to the laser pump input.

Testing...

Mk 2

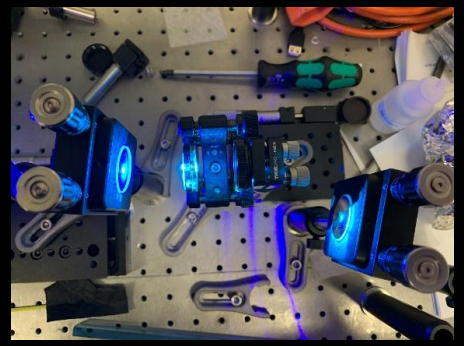


Jan 2019

Mk 3

Feb 2019

Mk 4

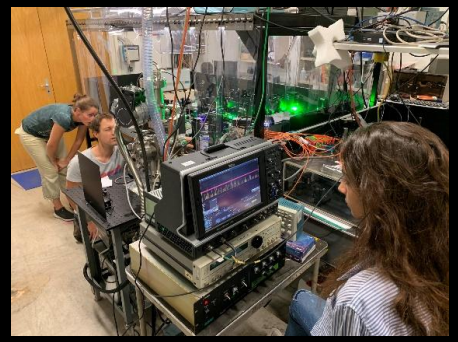


Feb 2019

Mk 5

Mar 2019

Mk 6



Jul 2019

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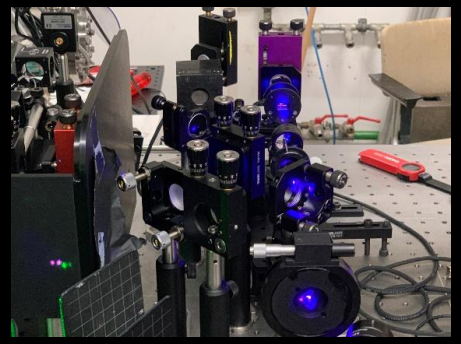

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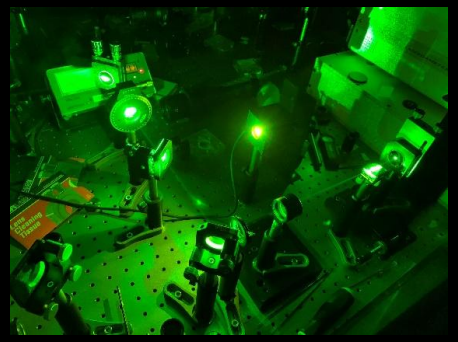

Jan 2020

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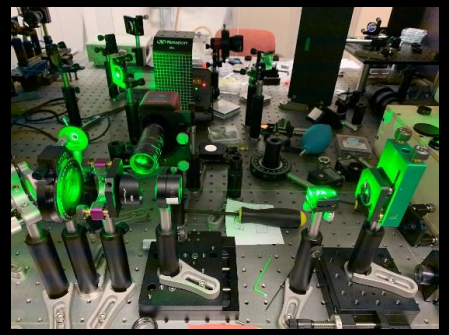

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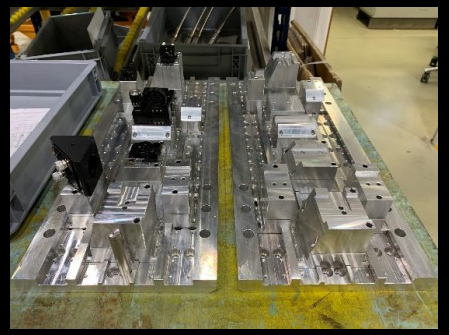
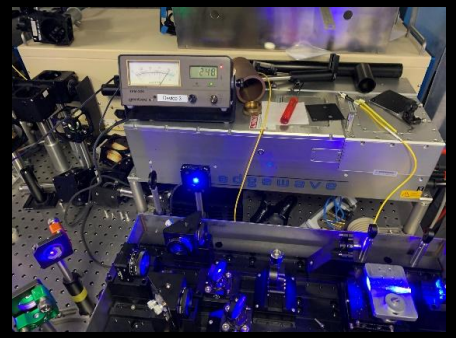


Aug 2020

Mk 11

Oct 2020

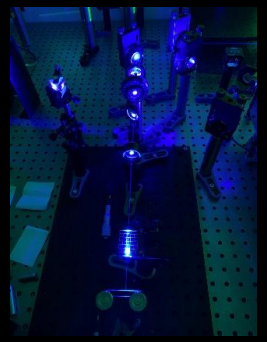
Mk 11



Nov 2020

And more testing...

Mk 12



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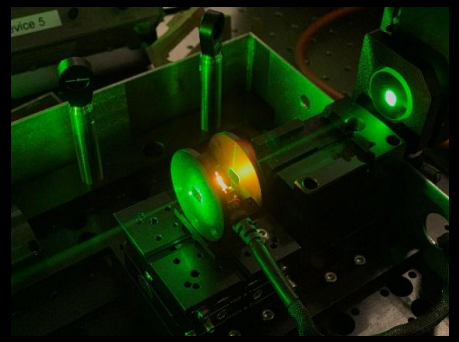

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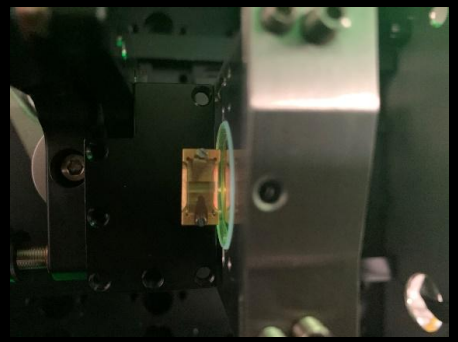
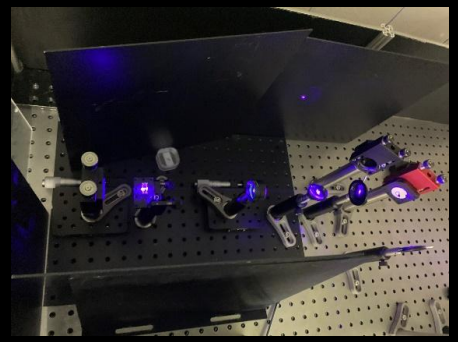


Jun 2021

Mk 13

Oct 2021

Mk 14



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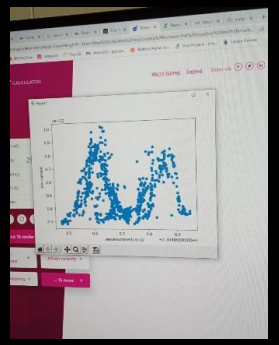

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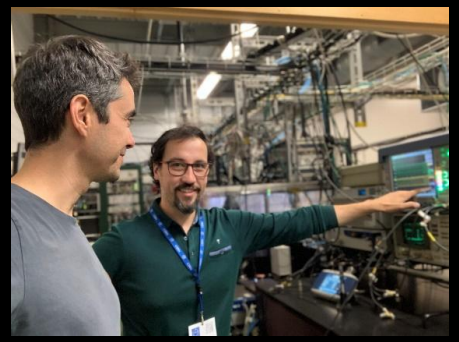

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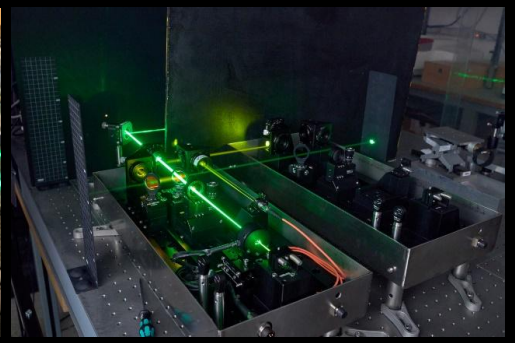

Jan 2023

Mk 17

Jan 2024

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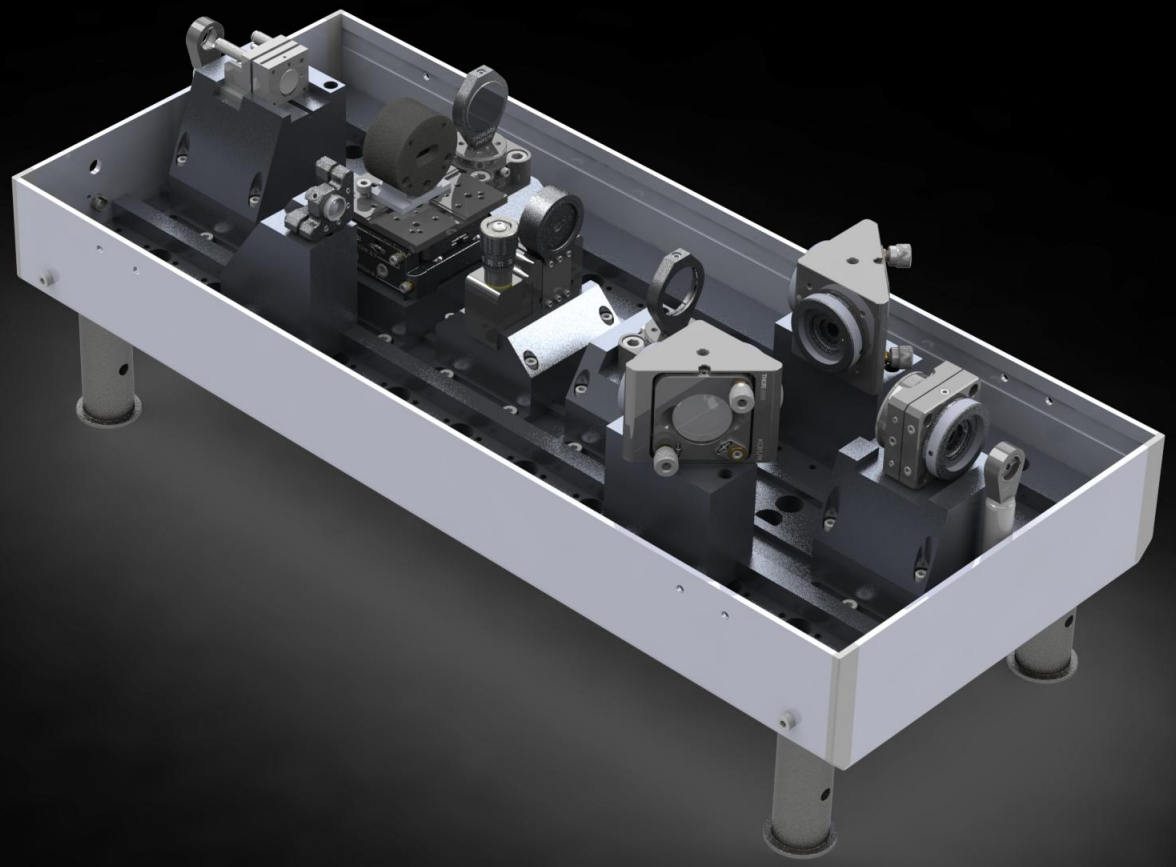
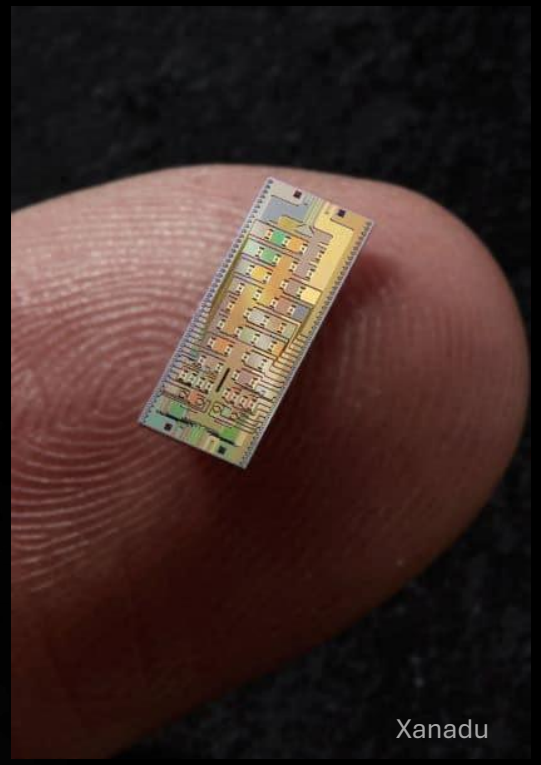
Delivery of the 1st prototype in August 2025

lighteye

The dream?





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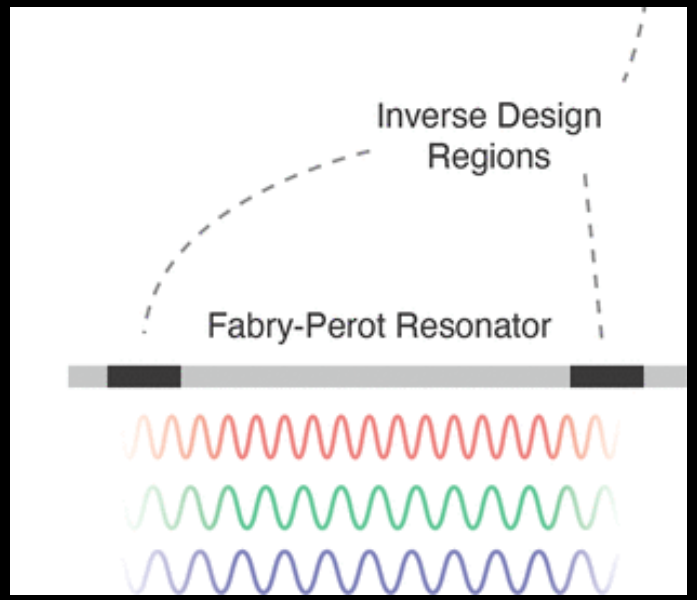
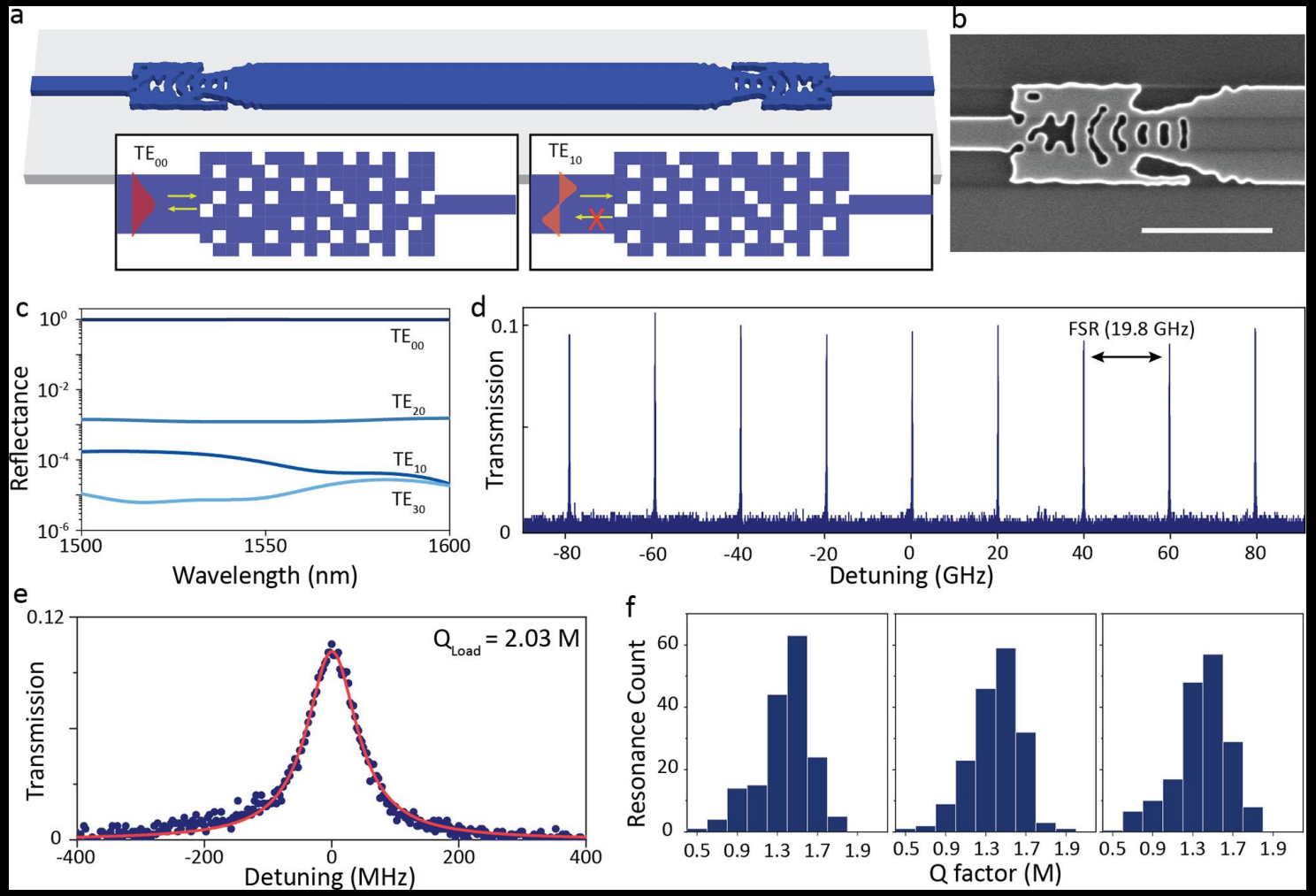
Revolutionary for optical communications and quantum computing

Can Photonic Integrated Circuit and *inverse* design be the path forward?





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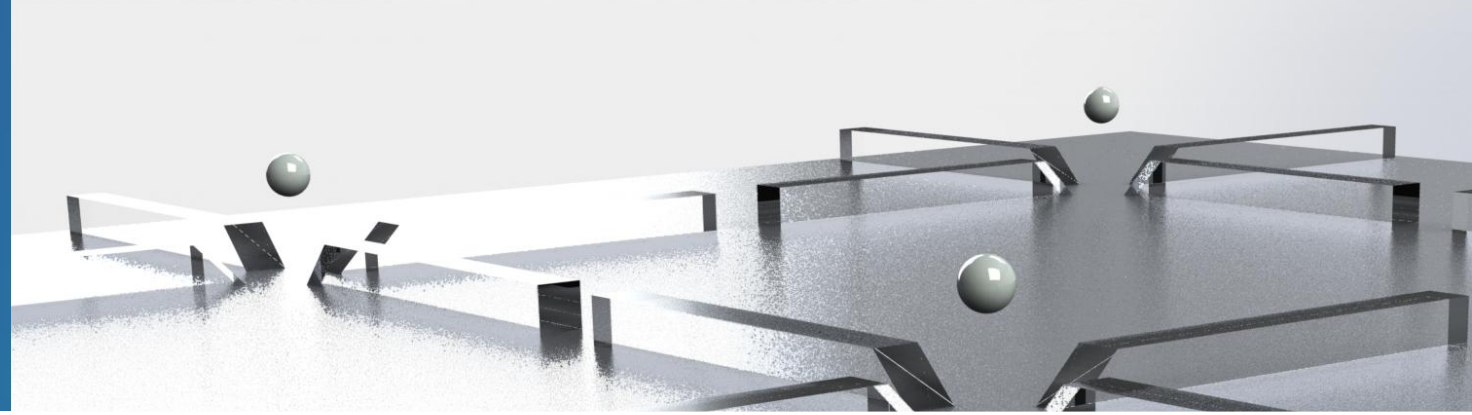
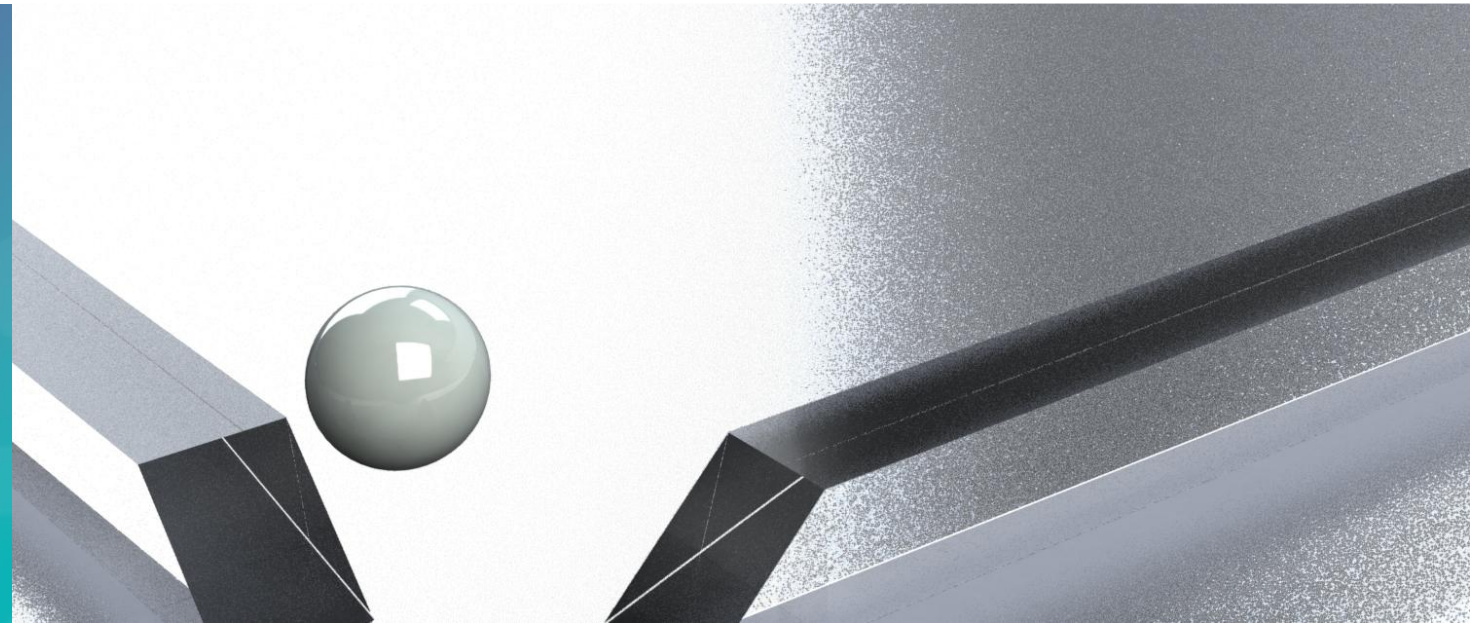
Thank you!