Technology Transfer Award

For research that resulted in a technological solution with wide-spread and/or significantly measurable societal utilization, with related impact on a global challenge or issue.

National Institute of Standards and Technology
U.S. Department of Commerce

OCTAVE PHOTONICS

Pioneering nonlinear nanophotonic systems to revolutionize laser science, quantum sensing, and optical signal processing

NAME OF PRINCIPAL INVESTIGATOR(S) OR TEAM:

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NOMINATION ABSTRACT:

Since their invention in 1999, the field of femtosecond laser frequency combs has exploded. Frequency combs are ultrafast laser systems whose spectrum is made up of a comb of laser beams at regularly spaced frequency intervals that can be used as a frequency ruler to perform precision frequency measurements with exquisite accuracy and stability. Frequency combs enable applications like optical atomic clocks, low-noise microwave generation, high-sensitivity gas detection, searches for exo-planets, and more. While the capabilities of frequency combs are extraordinary, their integration into applications is limited by their size, expense, power consumption, and complexity. Microcombs are miniaturized versions of optical frequency combs that are poised to revolutionize laser applications owing to their compact size, low weight, and low power consumption. Through pioneering microcomb research, the team of Drs. Jennifer Black, Travis Briles, David Carlson, Daniel Hickstein, Zachary Newman, and Scott Papp has invented methods to shrink laser frequency combs from large-scale laboratory systems to portable microfabricated devices and has led the use of these microcombs in numerous innovative applications. They have also pioneered the adoption of new materials with enhanced nonlinearity and improved fabrication capabilities.

The team's advances to the field are being adopted for applications in laser science, precision frequency measurement for optical atomic clocks, quantum sensing, and optical signal processing. Use cases continue to grow as the devices become smaller, less expensive, and more capable. The team's work has also advanced the much broader and rapidly growing field of nonlinear nanophotonics, which is poised to revolutionize laser science and applications. Integrated photonic circuits can provide precise control of a laser's optical spectrum in a nanofabricated package, allowing highly specialized laser systems to be constructed with unprecedented compactness and robustness for applications. The team is recognized for their work at the forefront of the competitive fields of microcombs and integrated photonics and the transfer of this highly applied work to industry.

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THE BACKGROUND CONTEXT SHAPING THE NEED AND INTEREST IN THIS RESEARCH.

Since their invention in 1999, the field of femtosecond laser frequency combs has exploded, and the National Institute of Standards and Technology (NIST) has been at the forefront of the field's developments. Frequency combs are ultrafast laser systems that emit a steady stream of femtosecond pulses at a highly stable repetition rate. When viewed in terms of their frequency spectrum, frequency combs are made up of a comb of laser beams at regularly spaced frequency intervals that can be used as a ruler to perform precision frequency measurements with exquisite accuracy and stability. Frequency combs enable applications like optical atomic clocks, record-breaking low-noise microwave generation, high-sensitivity gas detection, searches for exo-planets, and more. While the capabilities of frequency combs are extraordinary, their integration into applications has been limited by their size, expense, power consumption, and complexity. Microcombs are miniaturized versions of optical frequency combs that are poised to revolutionize laser applications owing to their compact size, low weight, and low power consumption.

Microcombs are a hot research topic worldwide because of their wide range of potentially disruptive applications, including in telecommunications, spectroscopy, and metrology. For telecommunications, for example, microcombs can be used to multiplex signals into optically interconnected data channels for parallel information processing. For metrology, microcombs have been used to shrink the optical infrastructure needed to operate optical clocks, which are poised to redefine the second in the International System of Units. Through pioneering microcomb research, the team recognized by this nomination has invented methods to shrink laser frequency combs from large-scale laboratory systems to portable microfabricated devices and has led the use of these microcombs in numerous innovative applications.

They have also pioneered the adoption of new materials with enhanced nonlinearity and improved fabrication capabilities. The team's advances to the field are being rapidly adopted for applications in laser science, precision frequency measurement for optical atomic clocks, quantum sensing, and optical signal processing. Use cases continue to grow as the devices become smaller, less expensive, and more capable. The team's work has also advanced the much broader and growing field of nonlinear nanophotonics, which is poised to have an even greater impact on technology. Nonlinear nanophotonics systems stand to revolutionize laser science and applications. Integrated photonic circuits can provide precise control of a laser's optical spectrum in a nanofabricated package, allowing highly specialized laser systems to be constructed with unprecedented compactness and robustness for applications like precision metrology, microresonator frequency comb generation, optical signal generation and processing, sensing, navigation, and the generation and manipulation of quantum information. Replacing free-space optical subsystems with integrated photonics modules not only reduces the size of a laser system for an existing application, but it can also enable new applications that arise from new physics that is accessible with these systems.

In integrated photonics devices, laser light can be confined to very small mode diameters in tightly confined nonlinear optical waveguides of less than a micron in width. The small widths of the waveguides and high intensities of the light achieved in these systems enhances the optical nonlinearity beyond what is achievable in conventional free-space optics. The team of Drs. Jennifer Black, Travis Briles, David Carlson, Daniel Hickstein, Zachary Newman, and Scott Papp are recognized for their work at the forefront of the highly competitive fields of microcombs and integrated photonics and the transfer of this highly applied work to industry. All the nominees have performed research together at various times in the NIST Time and Frequency Division in the Quantum and Nonlinear Nanophotonics Group. In 2019, Drs. Carlson and Newman moved on from their appointments at NIST to establish a spinoff company called Octave Photonics that has focused on commercializing the technologies. Dr. Hickstein joined Octave Photonics shortly after the company was established to serve as their first Principal Scientist. Octave Photonics was founded based on work done with NIST, and Octave Photonics continues to collaborate with NIST on projects. But the work at Octave Photonics has expanded into new areas, finding new applications and multiple new collaborators. They have become industry leaders in the development and packaging of highly ruggedized photonic integrated circuits, which are revolutionizing optical technology.

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NIST NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY U.S. DEPARTMENT OF COMMERCE

THE COMPELLING FACETS OF THE, OR THIS TEAM/PERSON'S, RESEARCH AND WHAT WAS THE ULTIMATE KNOWLEDGE AND INSIGHT DISCOVERED.

Arguably, the most significant technical breakthrough at the heart of the NIST-Octave Photonics collaboration was the development at NIST of self-referenced frequency combs based on high-efficiency silicon-nitride waveguides on a chip, which was published in Optics Letters in 2017 when Dr. Carlson was a postdoctoral research fellow at NIST [D. R. Carlson et al., "Self-referenced frequency combs using high-efficiency silicon-nitride waveguides," Optics Letters 42, 2314, (2017)]. This work is credited with multiple breakthroughs that identified the path to get a factor of ten or more reduction in the optical power required for self-referencing. Self-referencing is a technique that is almost always used to stabilize the output spectrum of a frequency comb, and it does so by effectively locking the high-frequency end of a frequency comb's output to the frequency-doubled low end of the spectrum. For the process to work, the output spectrum of a frequency comb must be broadened into a supercontinuum that spans a full octave of range (a factor of two in width). Then the low-frequency region of the spectrum can be frequency doubled and interfered with the high-frequency end of the spectrum to stabilize the comb frequencies.

Traditionally, the needed spectral broadening has always been done with bulk nonlinear optical materials or long optical fibers, but by fabricating short waveguides only a centimeter in length with highly nonlinear materials instead, the broadening can be performed with very low power, eliminating the need for light amplification, and dramatically simplifying frequency comb setups for applications. By itself, this achievement in supercontinuum generation would already be a very significant technical breakthrough, but the accomplishments in this one paper go further than this. The team also showed that by pumping a silicon nitride waveguide with higher optical powers, they could simultaneously create a supercontinuum and also perform third-harmonic generation on the supercontinuum, enabling self-referencing in a single nonlinear optical component, thus simplifying the comb spectrum stabilization even more. Another transformative innovation at the root of the partnership between NIST and Octave Photonics was the invention of the use of the material tantalum pentoxide (tantala) for use in fabricating nonlinear nanophotonic devices. Tantala offers low stress, low optical loss, and efficient nonlinear processes and is poised to play a growing role in the development of new integrated photonics devices and systems. The use of tantala enables high-performance nonlinear photonics devices to be created at lower cost and higher yield than other existing technologies. A patent for tantala ring resonators was awarded to team members in 2020 [Tantala ring resonator and method for fabricating nonlinear photonics devices, US20210055627A1, 2020], and tantala waveguides have been used to generate the broadband supercontinuum needed for self-referencing [Lamee et al., Nanophotonic tantala waveguides for supercontinuum generation pumped at 1560 nm, Optics Letters (2020)]. This work has been commercialized by Octave Photonics and forms the basis of one of their most widely used products. These devices make the technology of frequency comb stabilization accessible to a broad base of users outside of the academic laboratories. A current focus of the team's collaborative research has been on expanding the performance and applications of microcombs and nonlinear nanophotonics using innovative new materials, microfabrication techniques, and control schemes.

> **"This award shows what is possible when world class science, state of the art fabrication facilities, and a vibrant industry ecosystem intersect to turn a proof of concept into a commercial product," said Marla Dowell, Director of CHIPS Metrology Program and NIST Boulder Laboratory. "Frequency combs began as bulky lab equipment, and now they can be built into chip-scale devices which are changing technology from communications to quantum sensing and atomic clocks. This award recognizes an amazing Colorado team for their pioneering advances in integrated photonics and highlights the power of NIST-industry partnerships."**
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> **- Marla L. Dowell, Ph.D.**
> **Director, CHIPS Metrology Program and NIST Boulder Laboratory**
> **U.S. Department of Commerce**

HOW THIS RESEARCH HAS BEEN APPLIED, UTILIZED, COMMERCIALIZED OR OTHERWISE ADOPTED OUTSIDE THE LAB

The co-founders and principal scientist that form the leadership team at Octave Photonics each spent many years as researchers at NIST and the University of Colorado before Octave was launched in 2019. The strength of the long-term collaboration is evident in the publication records of Octave's staff: David Carlson, Daniel Hickstein, and Zach Newman have published 33, 22, and 10 papers with NIST staff in the peer-reviewed literature, respectively.

Octave Photonics has drawn from innovations from this body of work to develop products, and they continue to collaborate with NIST on new research proposals aimed at creating even more uses of integrated nonlinear nanophotonics. A few lines of research that have already resulted in commercial products and hold the potential for new applications are highlighted below. Electro-optic frequency combs for precision spectroscopy, including the search for exoplanets: Cutting-edge applications of femtosecond-laser frequency combs, such as astronomical spectrograph calibration and high-speed data transfer, require lasers with repetition rates of 10 GHz and above, far higher than the 100 MHz typical of femtosecond lasers. Light sources that are ultrafast and ultra-stable enable applications like timing with sub-femtosecond precision and control of quantum and classical systems. The standard source for such work is the mode-locked frequency comb, but in 2018, team members showed how a continuous-wave laser could be modulated at frequencies of over 10 GHz, providing a robust, flexible, and stable frequency comb at ultrahigh repetition rates in a much simpler and more flexible package called an electro-optic comb [Carlson et al., Science 361 (2018)]. This breakthrough has also been commercialized by Octave Photonics and has led to new applications.

Low-power frequency comb stabilization: The stabilization of the spectra for optical frequency combs is usually accomplished by stabilizing two parameters: the mode spacing and what's known as the carrier-envelope offset frequency. The mode spacing stabilization can be relatively easily accomplished by detecting the laser beat spectrum on a photodiode and stabilizing it to a microwave signal. But stabilizing the carrier-envelope offset frequency usually relies on a technique called f-2f interferometry, where the comb spectrum is broadened into a supercontinuum that spans more than an octave in frequency, and the low edge of the spectrum is frequency doubled to interfere with the high-frequency edge of the spectrum. As described in the previous section, the team has successfully fabricated integrated photonic waveguides at NIST that can lock the carrier-envelope offset frequency [D. R. Carlson et al., Optics Letters 42, 2314,(2017)], and products based on the approach have been successfully commercialized at Octave Photonics. Optical atomic clocks: Optical atomic clocks achieve remarkable accuracy, but their size and the use of bulk optical components prevent them from being more widely adopted in applications that require precision timing. By leveraging silicon-chip photonics, team members have contributed to the demonstration of a compact optical-clock architecture based on two-photon transitions in room temperature rubidium gas [Z.L. Newman, et. al., Optica 6, 680 (2019).] Team members have continued to revolutionize integrated photonic devices for optical clocks into higher-performance clock platforms and have recently turned their attention to optical lattice clocks based on strontium atoms, which require two stages of laser cooling with widely separated laser wavelengths to operate. The team was able to exclusively use metasurface optics coupled by fiber optics to generate the 12 separate cooling beams required for the two consecutive laser cooling stages. This demonstration was a dramatic simplification over prior methods of laser cooling alkaline earth atoms [A. R. Ferdinand et al., Arxiv:2404.13210, (2024)].
8) HOW HAS THIS RESEARCH "TRANSFERRED" AND BEEN APPLIED, UTILIZED,
COMMERCIALIZED OR OTHERWISE ADOPTED OUTSIDE YOUR LAB? (1000 words or less)
Please provide up to four references to any companies or partners utilizing this technology
or discovery.

Arbitrary optical synthesis: Integrated photonics provides a powerful tool for broadly reconfigurable designs and unparalleled nonlinearity at the chip-scale, offering an ideal platform for compact and scalable laser-wavelength conversion. NIST and Octave Photonics have collaborated to create new capabilities with integrated nonlinear photonic devices for laser-wavelength conversion that enable new technological applications. The team has used four-wave mixing in a nonlinear network to design devices that can translate the laser frequency by up 200 terahertz by design, with target frequencies of one hertz accuracy [J.A. Black, Z. L. Newman, S.-P. Yu, D. R. Carlson, and S. B. Papp, Physical Review X 13, 021027 (2022)]. Collaborations continue between NIST and Octave Photonics through several ongoing research programs.