Topical: Frequency Combs for Aerospace Applications

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Abstract

From their inception, frequency combs have enabled an array of exciting new applications in science. Combs can enable existing NASA priorities and present options for entirely new experiments leveraging the unique timing and frequency accuracy possible with this technology [1]. Experiments in space will require the development and qualification of an optical frequency comb platform compatible with harsh environments while maintaining low size, weight, and power. Space-deployable frequency combs will have a broad impact for NASA's next-generation precision frequency and timing applications.

Introduction

Over the past decade, frequency combs have become a critical enabling technology for precision measurement applications by providing the ability to extend attosecond-level timing of a part in 10^{19} frequency stability across the entire optical spectrum and into the microwave domain [1,2,3]. This unique capability has opened up an extraordinary range of sensors and novel sensing modalities. Of interest to NASA, frequency combs have been proposed in applications ranging from precision radial velocity measurements in the search for exo-planets [4], nanometer level distance measurement to support ultra-precise formation flying of satellites or detection of gravity anomalies [5-7], femtosecond time-transfer to synchronize millimeter astronomy telescope arrays [8], sensitive detection of greenhouse gasses [9], and as high-fidelity frequency dividers critical to optical clocks [10-12].

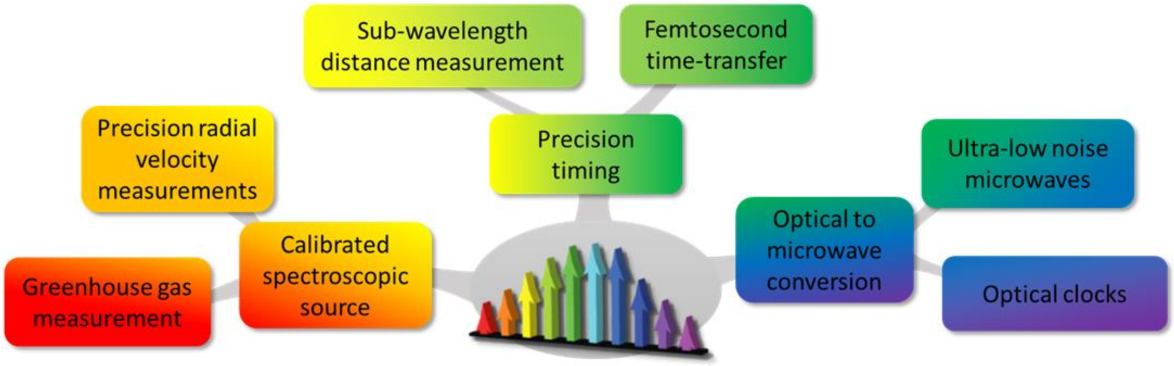

Figure 1. The emerging array of optical frequency comb applications in space.

While it is exciting to contemplate such experiments it is also important to ensure that the key underpinning technology in these applications, the optical frequency comb, will be able to support such measurements in the challenging environment of space. The two most important factors required to ensure the operation of frequency combs in space are first an increase in ruggedness to survive launches and ensure remote operation, and second, reducing the size, weight, and power (SWaP) of these optical systems so they can be operated on satellites. SWaP is particularly important since in most of the envisioned applications the comb will be just one required subsystem for the science and must not overwhelm the total instrument budget. In both of these regards, erbium fiber frequency combs are a particularly promising platform for a path to space. All polarization-maintained fiber designs have been shown to support compactness and long-term reliability [10,13] while still supporting $10^{-15}/s^{1/2}$ frequency stability and phase-slip free operation meeting the timing and fidelity requirements for nearly any comb application [11]. Fiber frequency combs have already been successfully launched on sounding rockets [10] and a mode-locked femtosecond fiber oscillator has been demonstrated in low Earth orbit [14]. While these missions are excellent first steps, there is more development to be done with regard to maturing existing radiation hardened designs, reducing SWaP, and decreasing the instability of these systems in the presence of harsh environmental conditions.

One of the driving factors of both SWaP and radiation sensitivity in these devices is the high optical pulse power and hence fiber amplifiers necessary to enable nonlinear frequency generation inherently required to stabilize the optical frequency comb [2]. Traditionally, highly doped erbium fiber amplifiers followed by highly nonlinear fibers are used to generate and spectrally broaden high-power pulses. The pump diodes required to drive these fiber amplifiers can consume over 10 W, or over half the power utilized by the entire comb. Additionally, the overall selection of available fibers to use in these systems is dramatically reduced compared to terrestrial comb systems, as the presence of germanium doping common to most telecommunication fibers is subject to increased loss in the presence of solar radiation. Recent advances with fiber-coupled nonlinear waveguides [15,16] by NIST and Octave Photonics have shown that the optical amplifier power levels can be dramatically reduced by confining the optical beams inside these customizable waveguides, where the efficiency of the optical frequency conversion is enhanced compared to traditional optical fibers. Besides the obvious SWaP reduction enabled by this technology, another advantage to these nonlinear waveguides is their inherent material resistance to the exposure of radiation. Recent collaborative efforts between NIST, Vescent Photonics, and Octave Photonics have focused on transitioning these technologies to the commercial sector.

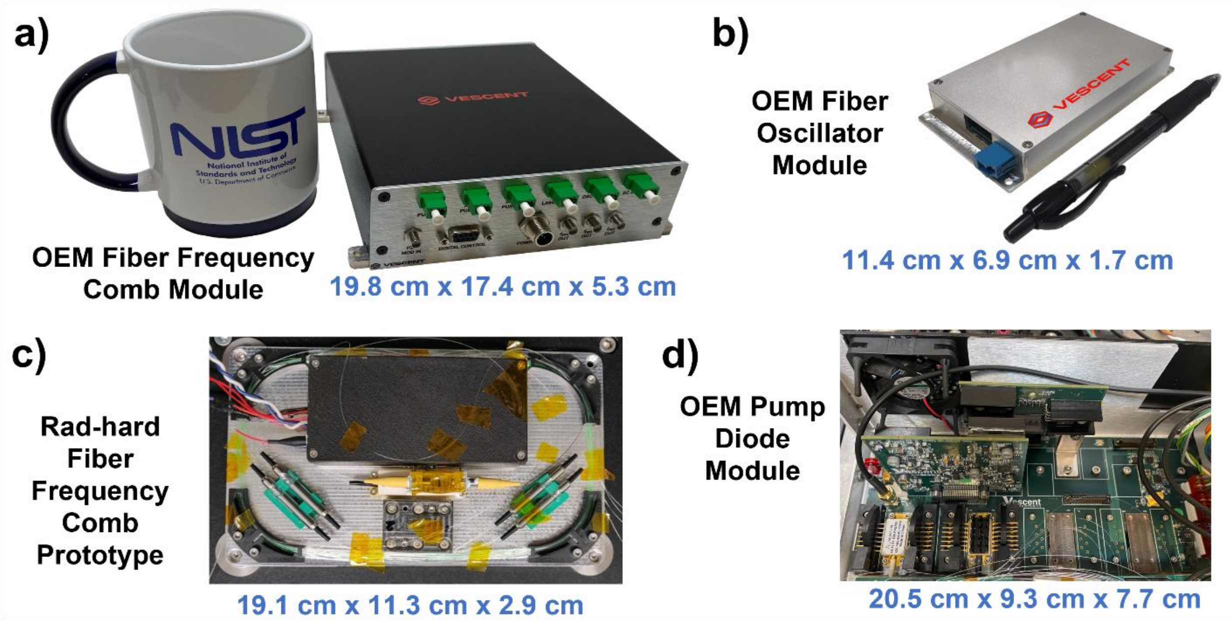

Figure 3a) Vescent's current fiber frequency comb module. Comb optics, photodetection circuits, and cavity oscillator length control circuitry are included. Pump diodes are not currently included in this packaging for thermal management reasons but are planned to be incorporated in future versions. b) Fiber oscillator module or the "engine" of the frequency comb system. This module contains optics and cavity length control actuators but does not include electronics or pump diodes. c) Prototype radiation-hardened fiber frequency comb developed under an Air Force BAA. Several of these systems are currently being evaluated for satellite deployment. This system includes an initial prototype of a nonlinear waveguide from Octave Photonics. d) Pump diode module for frequency comb applications. This unit contains current and temperature controllers and can house up to 4 diodes to drive two frequency comb systems.

Over the last 6 years Vescent has utilized SBIR and BAA grants to reduce the SWaP and cost of optical fiber frequency combs, as well as increase the ruggedness to environmental effects, specifically for deployed applications. A majority of the funding has come through the Air Force and NASA for eventual deployment of fiber combs to advance next-generation position, navigation, and timing (PNT) applications including optical atomic clocks and two-way time transfer. Some of this work has required the design, fabrication, and testing of radiation-hardened fiber frequency combs for deployment of a 2-photon rubidium clock on satellite platforms. While progress has been made to reduce SWaP and to get these systems outside of the laboratory, more effort is still necessary to get to sizes, power consumption, and overall ruggedness that will be suitable for CubeSat operation. The pathway to a comb platform for supporting cutting edge science is achievable through the continued development of radiation-hardened frequency combs and nonlinear nanophotonics.

Conclusion

While these efforts to develop low SWaP rad-hard combs have seen early success, there remains considerable work to achieve deployment on satellites. Further reduction of the system SWaP would be critical to supporting a CubeSat mission. Additionally, while frequency combs are ready to be flight tested, there have been no flights of this technology within the US, and only preliminary demonstrations in Europe and Asia. NASA efforts on both these fronts would be a boon for a host of future missions.

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