REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
20-01-2022	Final Report	1-May-2020 - 31-Oct-2021

4. TITLE AND SUBTITLE
Final Report: Facility For the Development and Characterization of New High-Performance Submillimeter Wave Lasers

5a. CONTRACT NUMBER
W911NF-20-1-0157

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611103

6. AUTHORS

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
Harvard University
Office for Sponsored Programs
1033 Massachusetts Ave 5th Floor
Cambridge, MA 02138 -5369

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
75673-EL-RIP.1

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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RPPR Final Report
as of 25-Jan-2022

Agency Code: 21XD

Proposal Number: 75673ELRIP **Agreement Number: W911NF-20-1-0157**
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DUNS Number: 082359691 EIN: 042103580N
Report Date: 31-Jan-2022 Date Received: 20-Jan-2022
Final Report for Period Beginning 01-May-2020 and Ending 31-Oct-2021
Title: Facility For the Development and Characterization of New High-Performance Submillimeter Wave Lasers
Begin Performance Period: 01-May-2020 **End Performance Period:** 31-Oct-2021
Report Term: 0-Other

Submitted By: Ph.D. Federico Capasso Email: capasso@seas.harvard.edu
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STEM Degrees: **STEM Participants:**

Major Goals: A facility for the development and characterization of submillimeter wave coherent sources (emitting from 100 GHz to a few THz) will be developed. It will enable major advances in this field such as new room-temperature sources and other devices such as modulators and receivers for important applications including chemical sensing and short-range communications in this underutilized frequency range. This facility will also support the effort of a new Army Research Office contract supporting the PI, aimed at developing a new type of sub-millimeter gas laser featuring compact room temperature operation, high brightness, broad tunability and much higher power than existing sources. A growing number of groups at Harvard have expressed interest in this frequency range for numerous applications. Students and postdocs from Harvard and other Universities will have access to this facility.
The facility will include a set of characterization equipment in the sub-THz frequency range for spectrally characterizing devices and materials in the sub-THz range by extending the coverage of spectrum analyzers and optical spectrometers, calibrated power-meters, as well as low-power sub-THz sources for research such as pump-probe spectroscopy of rotational levels of gas molecules. It will also greatly augment existing imaging instruments by integrating them with the new sources with the goal of large-scale sample characterization in the sub-THz range and for probing the near- and far-field of sub-THz sources. The facility will include the required instrumentation for this integration.
This facility will allow the following research to be performed at the PI's institution:
I. The characterization (frequency and power) of sub-terahertz sources and the characterization (frequency response, efficiency) of antennas, modulators and receivers in this frequency range.
II. The development of metasurfaces operating in the sub-THz range including lenses, polarizers, partially reflective surfaces and holograms.
III. The extension of the operating range of a scattering- Scanning Near-field Optical Microscope (housed in Harvard's Center for Nanoscale Systems user facility) to sub-THz frequencies by developing a compact sub-THz source (quantum cascade laser pumped sub-THz gas laser). This will enable among other new research in the rapidly evolving field of 2D materials and the development of devices working in this frequency range.

Accomplishments: Please see the uploaded PDF document.

Training Opportunities: All graduate students in the group of the PI have access to the facility and currently 3 students (2 graduate, 1 undergraduates) are trained to use some equipment from the facility.

Results Dissemination: Nothing to Report

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Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI
Participant: Federico Capasso Ph.D.
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
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Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Arman Amirzhan
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Partners

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I certify that the information in the report is complete and accurate:
Signature: Federico Capasso
Signature Date: 1/20/22 4:53PM

DURIP Project summary

Facility for the development and characterization of new high-performance submillimeter wave lasers

Contract number: W911NF-20-1-0157

PI: Prof. Federico Capasso

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The grant funds the acquisition of a "Facility for the development and characterization of new high-performance submillimeter wave lasers".

The facility is currently being built around radio frequency equipment such as spectrum analyzer and frequency generator and optical equipment such as Fourier transform infrared spectrometers and bolometers already existing and available in the PI laboratory. The facility will consist of various pieces of equipment aimed at characterizing materials or waveguides at tunable sub-THz frequencies, along with the characterization of sources (emission frequency, beam profile) and will also include the purchase of quantum cascade lasers to pump the molecular lasers. The equipment provided by the facility will also allow the development of a THz source based on the recently demonstrated quantum cascade laser pumped molecular laser (QPML) concept and using methyl fluoride (CH_3F) as the gain medium. Some equipment of this facility will be aimed at characterizing specific properties of THz sources using molecular lasers (such as probing the molecular gain medium by means of rotational spectroscopy).

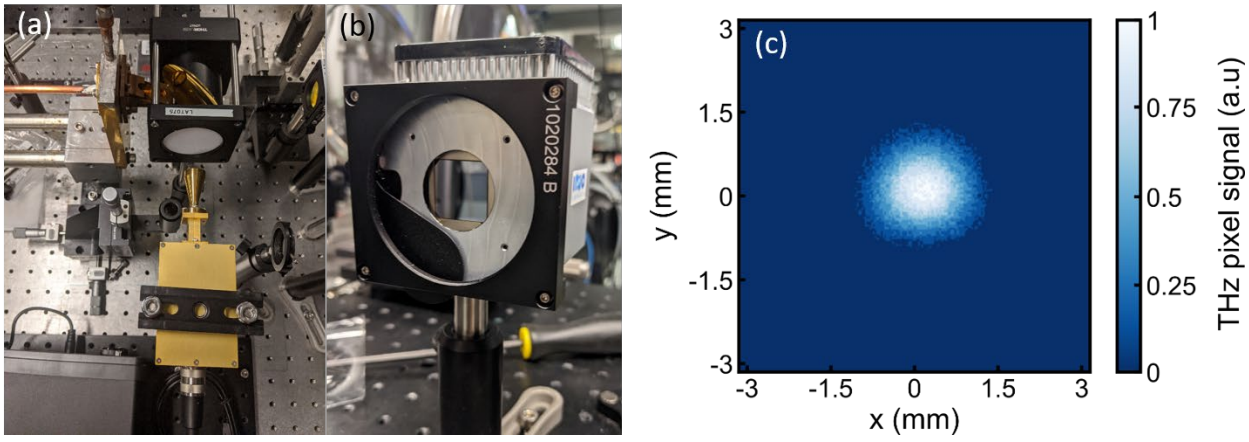

Figure 1 *Photograph of two set-ups showing the use of some of the purchased equipment for (a) Measurement of the output power of a THz laser (b) Measurement of the beam profile of a THz laser. (c) Experimental data measured with the THz camera of the focused spot emitted by a CH_3F QPML*

The most crucial piece of equipment brought by this facility is a calibrated THz power meter as depicted in Fig. 1(a) measuring the output power of a QPML. Another typical use case of this facility is demonstrated

in Fig. 1(b) showing the THz beam profiler (camera) of this facility imaging the output of a QPML. The measured beam profile of this QPML at 1 THz is shown in Fig. 1(c).

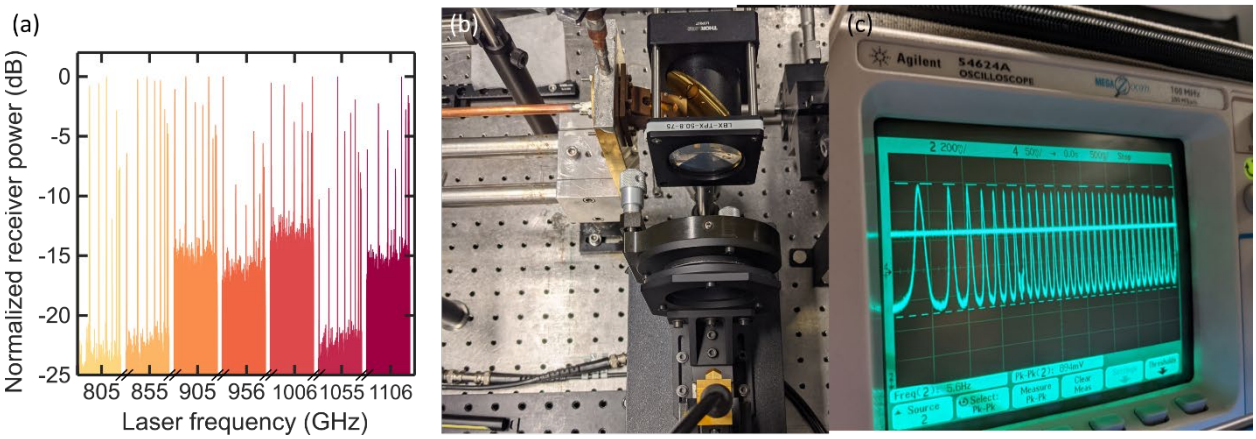

Figure 2 *(a) Emission lines of a CH3F QPML measured with the help of a heterodyne mixer provided by the funded facility. (b) Photograph of the Fabry-Perot scanning interferometer being used to measure the emission of a QPML. (c) Screenshot of the oscilloscope screen showing the detector signal while scanning the interferometer path difference. The high finesse fringes of the interferometer are a key feature for proper frequency measurement.*

In addition to the above equipment, we have received various pieces of equipment for in depth frequency characterization techniques, such as a heterodyne mixer working from 750 GHz to 1.1 THz and a scanning Fabry Perot interferometer. The heterodyne mixer allowed up to measure the emission frequencies of a QPML between 750 and 1.1 THz. Figure 2(a) shows 55 lines of a CH_3F QPML measured thanks to this new mixer. Additionally, the Fabry Perot interferometer (shown in Fig. 2(b)), has been used to verify high frequency emission of an NH_3 QPML. In inset of Fig. 2(b) is a screen shot of the oscilloscope showing high finesse Fabry-Perot fringes from this interferometer measured with a Schottky diode detector.

Finally, the characterization tools from this facility will help characterize QPML cavities and provide useful insight to scale up their output power. The facility will also be used to diagnose and study the gain medium by performing rotational spectroscopy and is already producing useful data. All graduate students in the group of the PI have access to the facility and currently 3 students (2 graduate, 1 undergraduates) are trained to use some equipment from the facility.

Through the targeted study of three different variables (power, beam profile, gain medium) the use of the facility will be key to the success of an ongoing ARO funded contract (contract number W911NF-19-2-0168, title: Widely-tunable, compact sub-millimeter source operating at room-temperature from 100 GHz to 1 THz), aimed at further developing the QPML concept into a compact, room temperature, widely tunable THz source. As part of this project, the PI has an ongoing collaboration with Prof. Henry Everitt (US Army CDCC Aviation and Missile Center), an expert in optically pumped far-infrared lasers and sub-terahertz spectroscopy. As part of this collaboration numerous sub-terahertz detectors and receivers, property of the US Army (Zero Bias Schottky diode detectors from 150 GHz up to 1.1 THz, Spectrum analyzer extensions from 250 to 750 GHz), are currently loaned to the PI. This facility complements but does not overlap with the existing capabilities offered by this collaboration.

Summary of the critical equipment that compose this facility

THz power meter: As characterizing the emission power is a key performance of a THz or sub-THz source, a calibrated power meter is essential. A very sensitive THz power meter from Virginia Diodes Inc. was purchased for this facility, as it includes a self-calibration mechanism using a built-in thermal source and provides a broadband spectral coverage.

THz beam profiler: A THz camera using a microbolometer array (INO Microxcam 384 THz) was purchased to characterize the output beam of THz sources. It will be used in the future to design efficient beam output coupler for the QPML source.

DFB-QCLs: We have purchased DFB-QCLs that will be used to make a reference QPML that could be used by others. The development of the QPML source using methyl fluoride is ongoing.

Mid-infrared and THz detectors: High bandwidth detectors used to measure the infrared pump light or emitted THz light have been acquired.

750-1.1 THz mixer: An additional spectrum analyzer extension covering the spectral region from 750 GHz up to 1.1 THz was purchased to complete our current frequency measurement capabilities. We used it to measure the frequency emission of a CH_3F QPML.

Scanning Fabry Perot interferometer: A scanning Fabry Perot interferometer was acquired. This piece of equipment allows us to measure frequencies between 100 GHz and 10 THz by using a broadband source such as a Golay Cell and scanning the interferometer's path difference.