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# Self-winding Helices as Slow-wave Structures for mm and sub-mm Travelling Wave Tubes

**Cavallo, Francesca**
**UNIVERSITY OF NEW MEXICO**
**1700 LOMAS BLVD NE**
**ALBUQUERQUE, NM,**
**US**

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**6. AUTHOR(S)**
Francesca Cavallo

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
UNIVERSITY OF NEW MEXICO
1700 LOMAS BLVD NE
ALBUQUERQUE, NM
US

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In the three years of the project, we made significant progress in predictive modeling, synthesis, and characterization of self-assembled SWSs for millimeter-through-THz vacuum electronic de-vices. This progress was made despite COVID-19 severely hampering our work by forcing labor-atories to be closed for 5 months and under limited operations for 10 additional months over the duration of the award.
Our accomplishments include
• a rapid assessment of the performance of cold and hot helices as their parameters vary in a practically realizable space by self-assembly of NMs. These parameters include di-ameter to pitch ratio, tape width (i.e., width of the NM strips or ribbons), surface rough-ness, substrate type, and the geometry of the enclosing waveguide of the helix.
• 3D simulation models and understanding of beam-wave interaction in self-assembled helices with single and double chirality;
• predictive models of the relaxation pathway of conductive ribbons into self-assembled helices;
• robust and mass-producible helices with high thermal conductance and electrical con-ductance and a novel approach to their fabrication based on self-assembly of conduc-tive ribbons during electroplating;
• a scalable device design that integrates a helical SWS and two “coaxial horn antennas” to couple radiation in and out of the helix;
• devices for on-wafer characterization of cold helices;
• a customized set-up for the characterization of cold helices up to 650 GHz;
• characterization of cold helices between 60 and 90 GHz;
• optimal designs for heat management;
• several refereed publications, patents, and invited and contributed talks at international conferences;
• training of students and post-docs via a cross-disciplinary and multi-institution mentoring program.

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# FINAL REPORT

**Project Title:** Self-winding Helices as Slow-wave Structures for mm and sub-mm Travelling Wave Tubes.
**Principal Investigator:** Francesca Cavallo, University of New Mexico, Albuquerque (NM).
**Co-Principal Investigators:** Max G. Lagally and Daniel W. van der Weide, University of Wisconsin-Madison, Madison (WI).
**Grant/Contract No.** FA9550-19-1-0086
**Reporting Period:** 04/01/2019-03/31/2022
**Program Manager:** Dr. John Luginsland
**Program:** Laser and Optical Physics
**Changes in research objectives, if any:** None
**Change in AFOSR program manager, if any:** Yes. The program manager changed from Dr. Pomrenke to Dr.Roach in year 1 of the project, from Dr. Roach to Dr. Pomrenke and then to Dr. Singleton in year 2 of the project, and from Dr. Singleton to Dr. Luginsland in year 3 of the project.
**Extensions granted:** None

## OVERVIEW OF THE PROJECT

This research program aims to establish a radically new concept for the realization of helical slow-wave structures (SWSs) that operate between 0.1 and 10 THz. The approach to miniaturizing helical SWSs for application beyond the microwave range relies on guided self-assembly of metal nanomembranes (NMs)[1] into helices.[2-3] This process enables batch fabrication of microscale and nanoscale-diameter structures with mesoscale length. The dimensions of the helices can be precisely manipulated by tailoring residual stress in an epitaxial or non-epitaxial NM, the stiffness of the NM, and the geometry of the NM in the plane perpendicular to its thickness.[2-9] The target NM materials are metals.

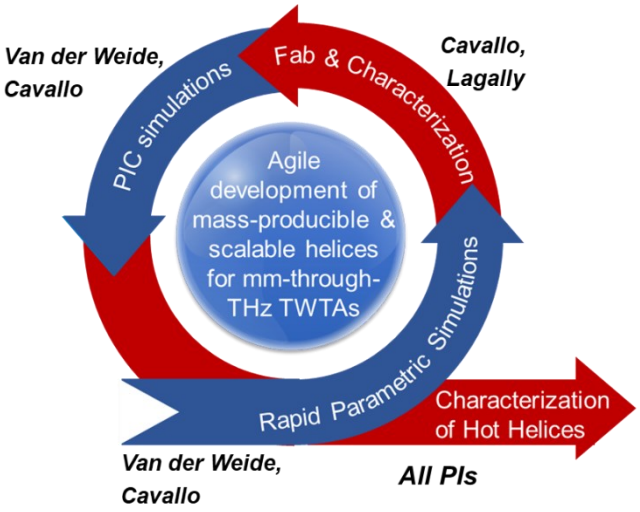


**Figure 1**. Iterative approach to obtain fully characterized self-assembled SWSs for mm-through-THz waves. The PIs involved in each area of the project are specified.

This comprehensive and synergistic theoretical, computational, and experimental effort addresses a fundamental-science question as well as major technical challenges:

- *Fundamental-science question:* what are the relationships between the performance of self-winding SWSs and the structure of the materials at the nanoscale?
- *Technical challenge:* scalable fabrication and predictive control of helical SWSs for millimeter-through-THz traveling-wave tube amplifiers (TWTAs).

- *Technology transfer challenge:* a shortage of fixturing and test equipment for rapid evaluation of the SWSs produced in this effort. We have a partnership with Tera-X, LLC, a small business with a Phase I SBIR that is working on this aspect.

A primary advantage of our team's work is the rapid characterization and feedback into the fabrication process that, in conjunction with the full-wave electromagnetic and particle-in-cell (PIC) simulations, will enable convergence onto a process and design that agree with simulation in tests of cold and hot helices. Figure 1 illustrates our iterative approach and specifies the PIs' involvement in each area of the project.

The **deliverables** of the program are:

- **a predictive capability of beam-wave interaction at varying attributes of the SWSs and the electron beam;**
- **a predictive capability of the geometry of self-assembled helices;**
- **mass-producible and structurally characterized helices;**
- **understanding and precise control of the NM structure-property relationship at rest and under typical operating conditions for a TWTA;**
- **a prototype device and a set-up for characterization of cold helices;**
- **a prototype device and a set-up for characterization of hot helices.**

## ACCOMPLISHMENTS

In the three years of the project, we made significant progress in predictive modeling, synthesis, and characterization of self-assembled SWSs for millimeter-through-THz vacuum electronic devices. This progress was made despite COVID-19 severely hampering our work by forcing laboratories to be closed for 5 months and under limited operations for 10 additional months over the duration of the award.

Our **accomplishments** include

- **a rapid assessment of the performance of cold and hot helices as their parameters vary in a practically realizable space by self-assembly of NMs. These parameters include diameter to pitch ratio, tape width (i.e., width of the NM strips or ribbons), surface roughness, substrate type, and the geometry of the enclosing waveguide of the helix.**
- **3D simulation models and understanding of beam-wave interaction in self-assembled helices with single and double chirality;**
- **predictive models of the relaxation pathway of conductive ribbons into self-assembled helices;**
- **robust and mass-producible helices with high thermal conductance and electrical conductance and a novel approach to their fabrication based on self-assembly of conductive ribbons during electroplating;**
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- **devices for on-wafer characterization of cold helices;**
- **a customized set-up for the characterization of cold helices up to 650 GHz;**
- **characterization of cold helices between 60 and 90 GHz;**
- **optimal designs for heat management;**
- **several refereed publications, patents, and invited and contributed talks at international conferences;**

- **training of students and post-docs via a cross-disciplinary and multi-institution mentoring program.**

Detailed information about these topics can be found in our published work, previously provided annual reports, and informal progress reports and manuscripts draft provided to the program manager.

## PRODUCTS

*Submitted Manuscripts*

- M. A. Martinez, S. Hajitabarmarznaki, D. J. Prakash, M. G. Lagally, D. W. van der Weide, F. Cavallo, **Amplification of THz Waves via Beam-Wave Interaction in Self-Assembled Helical Slow-Wave Structures with Single and Double Chirality,** Submitted to *Applied Physics Letters*.

*Manuscripts in Preparation*

- A. Chaudhary, D. J. Prakash, D. W. van der Weide, M. G. Lagally, and F. Cavallo, **Tailoring Reconfiguration of Ultra-Compliant Ribbons by Electrodeposition of Stressed Films,** Manuscript in preparation for *Small.*
- D. J. Prakash, H. Dibaji, M. L. Debasu, D. E. Savage, M. G. Lagally, and F. Cavallo, **Relaxation Pathways of Metal Ribbons for Applications in High-Frequency Vacuum Electronic Devices**, Manuscript in preparation for *Advanced Functional Materials.*

*Refereed Journal Articles*

- D. J. Prakash, M. M. Dwyer, M. M. Argudo, M. L. Debasu, H. Dibaji, M. G. Lagally, D. W. van der Weide, F. Cavallo, **Self-Winding Helices as Slow-Wave Structures for Sub-Millimeter Traveling-Wave Tubes**, ACS Nano 2021, 15, 1, 1229–1239.

*Refereed Conference Proceedings*

- D. J. Prakash, M. Martinez Argudo, S. Hjitabarmarznaki, Daniel W. van der Weide, and Francesca Cavallo, **Design and Fabrication of Devices for Characterization of Cold Parameters in Self-Assembled Slow-Wave Structures**, 23rd IEEE International Vacuum Electronics Conference (IVEC), In Press.
- D. J. Prakash, M. M. Argudo, D. W. Van der Weide and F. Cavallo, **Design and Fabrication of Self-Assembled Metal Helices for Millimeter-through- THz Traveling Wave Tube Amplifiers**, 2021 14th UK-Europe-China Workshop on Millimetre-Waves and Terahertz Technologies (UCMMT), 2021, 1-3.
- M. Martinez Argudo, D. J. Prakash, F. Cavallo, and D. W, van der Weide, **Modeling of Self-Winding Helices for Sub-Millimeter Traveling Wave Tube Amplifiers**, 2021 14th UK-Europe-China Workshop on Millimetre-Waves and Terahertz Technologies (UCMMT), 2021, 1-3.

*Invention Disclosures*

- S. A. Scott, F. Cavallo, S. Hajitabarmarznaki, D. W. van der Weide, M. G. Lagally, D. J. Prakash, **Helical Slow-Wave Structures with Integrated Couplers of THz Radiation: Devices and Methods of Fabrication**, March 2022.

*Patents*

- M. M. Dwyer, F. Cavallo, D. W. van der Weide, M. G. Lagally, A. Bhat, **Traveling Wave Tube Amplifier Having a Helical Slow-Wave Structure Supported By a Cylindrical Scaffold**, U.S. Patent No. 11,201,028 B2, December 14th, 2021

*Patent Applications*

- A. Chaudhary, F. Cavallo, D. W. van der Weide, M. G. Lagally, D. J. Prakash, **Directed Self-Assembly of Helices via Electrodeposition on End-Tethered Nanoribbons For Millimeter Wave Traveling Wave Tube Amplifiers**, U.S. Provisional Patent Application No. 63/342383, filed on May 16th 2022.
- M. M. Dwyer, F. Cavallo, D. W. van der Weide, M. G. Lagally, A. Bhat, D. J. Prakash, **Electroplated Helical Slow-wave Structures for High-frequency Signals**, U.S. Patent Application No. 16/882,591, May 25th, 2020.

*Invited Talks*

- Cavallo, F., **Design and Fabrication of Self-Assembled Metal Helices for Millimeter-through-THz Traveling Wave Tube Amplifiers**, 14th UK, Europe, China Millimeter Waves and Terahertz Technology Workshop, 13-15 September 2021, Virtual Meeting.
- Cavallo F., **Synthesis, Processing, and Structure-Property Relationships of Inorganic Sheets for Infrared and THz Waves**, 2021 IEEE Photonics Society Summer Topical Meeting Series, July 19-21, Virtual Meeting.

*Accepted Abstracts at International Conferences*

- A. Chaudhary, D. J. Prakash, S. Hjitabarmarznaki, Daniel W. van der Weide, M. G. Lagally, and Francesca Cavallo, **Electroplated Helical Slow-wave Structures for Millimeter-through-THz Vacuum Electronic Devices**, 64th Electronic Materials Conference, Columbus (OH), June 29-July 1, 2022.

*Contributed Abstracts at International Conferences*

- D. J. Prakash, M. Martinez Argudo, S. Hjitabarmarznaki, Daniel W. van der Weide, and Francesca Cavallo, **Design and Fabrication of Devices for Characterization of Cold Parameters in Self-Assembled Slow-Wave Structures**, 23rd IEEE International Vacuum Electronics Conference (IVEC), Monterey (CA), April 25-29 2022.
- M. Martinez Argudo, D. J. Prakash, F. Cavallo, and D. W. van der Weide, **Modeling of Self-Winding Helices for Sub-Millimeter Traveling Wave Tube Amplifiers**, 14th UK, Europe, China Millimeter Waves and Terahertz Technology Workshop, 13-15 September 2021, Virtual Meeting.

- M. Martinez Argudo, D. J. Prakash, D. van der Weide, and F. Cavallo, **Parametric Modeling of Self-Winding Helices for Sub-Millimeter Traveling Wave Tube Amplifiers**, 63rd Electronic Materials Conference, Virtual Meeting, June 23-25, 2021.
- *D. J. Prakash, H. Dibaji, M. L. Debasu, D. E. Savage, M. G. Lagally, and F. Cavallo,* **Competing Self-Assembly Pathways for Metal Nanomembranes**, 2021 Virtual MRS Spring Meeting 2021, April 17-23.
- *S. H. Dibaji, D. J. Prakash, M. M. Dwyer, S. A. Scott, D. W. van der Weide, M. G. Lagally, and F. Cavallo,* **Self-winding Helices as Slow-wave Structures for THz Frequencies**, 62nd Electronic Materials Conference, Ohio State University, Columbus (OH), June 24-26, 2020.