Intelligent Material Classification with a Silicon-Based Millimeter-Wave Frequency Comb Receiver

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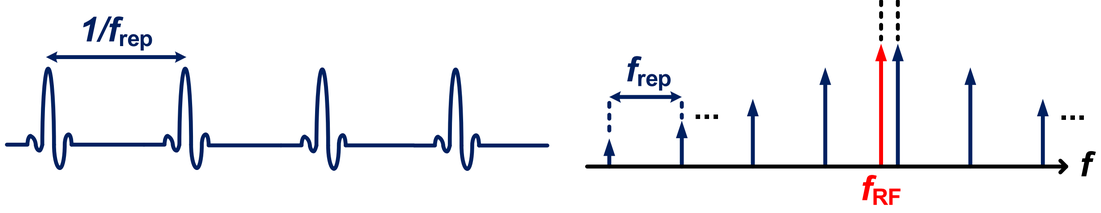
1. Objectives

- Intelligent characterization of different materials with radio-frequency (RF) and millimeter-wave (mm-wave) signals

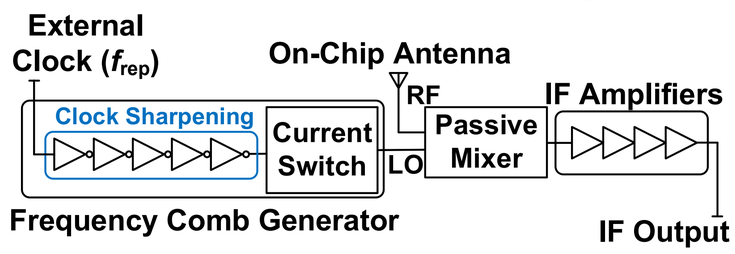
More Frequency Components ➡ More Spectral Information ➡ Higher Accuracy in Classification ➡ A Broadband Multi-Tone Frequency Comb

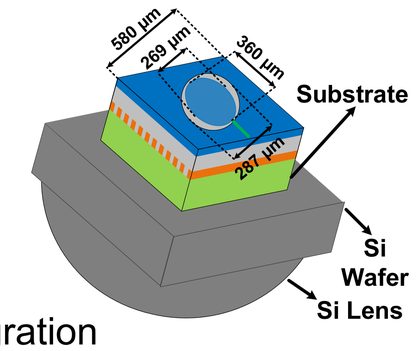
- A frequency comb covers a wide range with tunable intervals
- A heterodyne receiver with a comb reference records broadband spectral information in a single shot
- Using a silicon-based integrated circuit for a small form factor
- Supervised machine learning tools are used to classify the measured spectral data



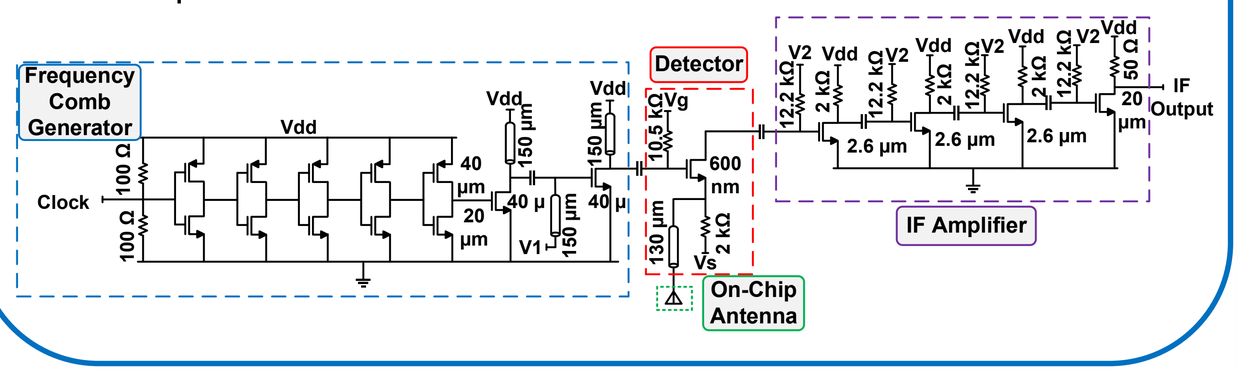
2. Broadband Comb Receiver

- Coherent detection of the received signal by mixing it with an ultrashort pulse train (frequency comb)



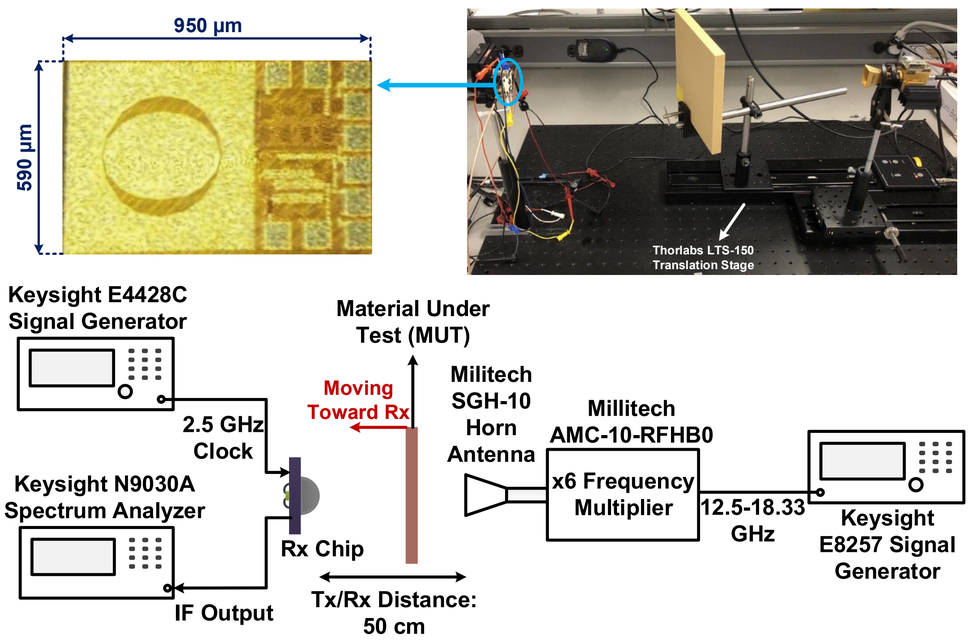


- A broadband on-chip antenna for full integration
- Complete circuit schematics:

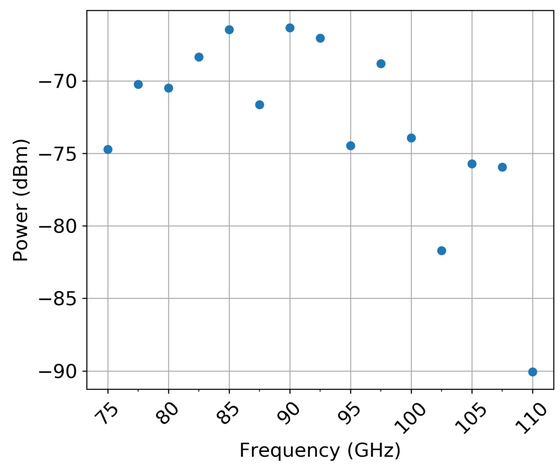


3. Multi-Spectral Transmission Measurements

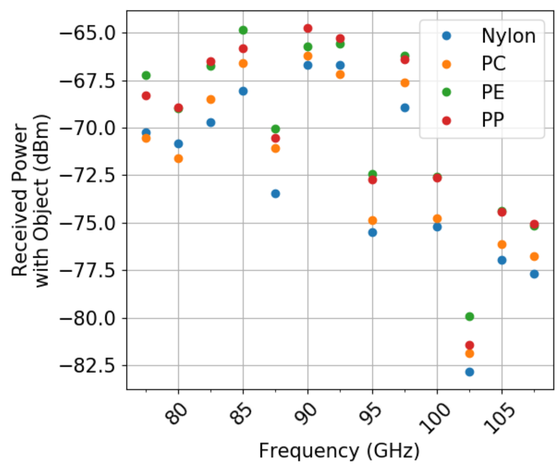
- The chip micrograph and the experimental setup:



- Materials under test: 1) Polyamide Nylon 66 $(C_{12}H_{22}N_2O_2)_n$ 2) Polyethylene $(C_2H_4)_n$ 3) Polycarbonate $C_{15}H_{16}O_2$ 4) Polypropylene $(C_3H_6)_n$
- Received signals in the W-band without any material under test:



- Received signals after placing 0.5” slabs made of these four materials:

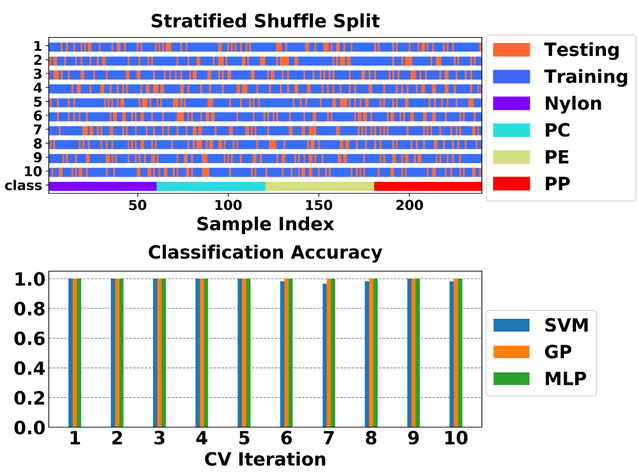


4. Classification Results

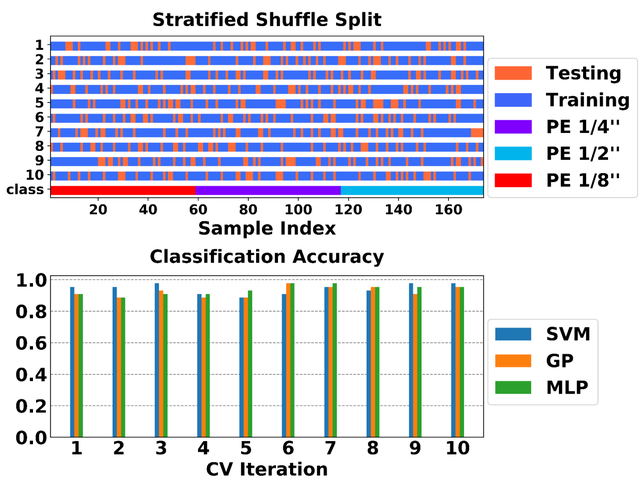
- Three supervised learning tools from the Scikit-Learn library were used for classifying the materials based on their broadband mm-wave transmissions:

  1) Support Vector Machine (SVM), 2) Multi-Layer Perceptron neural network, 3) Gaussian process classifier
- Cross-validation is performed to verify consistency among various training data sets
- In every CV iteration, 75% of the data is used for training and for testing

- Material classification accuracy:



- Thickness classification accuracy:



5. Summary

- A miniaturized solution for broadband sensing and wireless characterization of materials
- Fabricated in the TSMC 65-nm CMOS process
- Frequency combs introduce more spectral bandwidth with extra tunability
- More frequencies result in higher accuracy
  - More physical information
  - Less prone to noise and false detections
- Multiple supervised learning classifiers result in high classification accuracies in detecting the material type and thickness of a slab

References

[1] B. Jamali and A. Babakhani, "A Fully Integrated 50–280-GHz Frequency Comb Detector for Coherent Broadband Sensing," in IEEE Transactions on Terahertz Science and Technology, Nov. 2019.

[2] B. Jamali, D. Ramalingam, and A. Babakhani, “Intelligent Material Classification and Identification Using a Broadband Millimeter-Wave Frequency Comb Receiver," in IEEE Sensors Letters, July 2020.