

# Broadband Spectroscopy of Materials with an Integrated Comb-Based Millimeter-Wave Detector

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**Abstract**—A miniaturized broadband spectroscopic sensor using a fully integrated millimeter-wave detector is presented. The detector chip generates a frequency comb with a tunable spacing as a reference to downconvert received signals. By tuning the comb spacing, the detector can detect frequency tones from 50 GHz to 155 GHz with a resolution only limited to the linewidth of comb tones. A spectroscopy setup including the detector and four sheets made of different materials is implemented to characterize the frequency response of materials in this frequency range.

## I. INTRODUCTION

Various objects absorb and scatter electromagnetic waves in different ways depending on their shapes, material composites, and thicknesses, among several parameters. Spectroscopy systems in microwave and millimeter-wave (mm-wave) frequencies intend to distinguish materials based on their responses to electromagnetic waves at different frequencies [1], [2]. Broadband wireless systems in these frequencies make it feasible to characterize objects over a wide range of frequencies using one single solution. Furthermore, a silicon-based integrated solution miniaturizes this broadband spectroscopy system on a small mm-sized chip with low fabrication cost.

In this work, a frequency-comb-based mm-wave detector is presented to measure the response of different objects to radiated waves over a wide range of frequencies. A frequency comb is generated on the chip which can downconvert received tones to intermediate frequencies (IF). This fully integrated solution in silicon incorporates an on-chip antenna, a frequency comb generation circuit, a heterodyne FET mixer, and an IF amplifier chain. Received frequency tones from 50 GHz to 155 GHz are measured with and without the presence of four different objects to measure their responses to electromagnetic waves within this frequency range.

## II. BROADBAND DETECTOR

The concept and architecture of the comb-based detector is

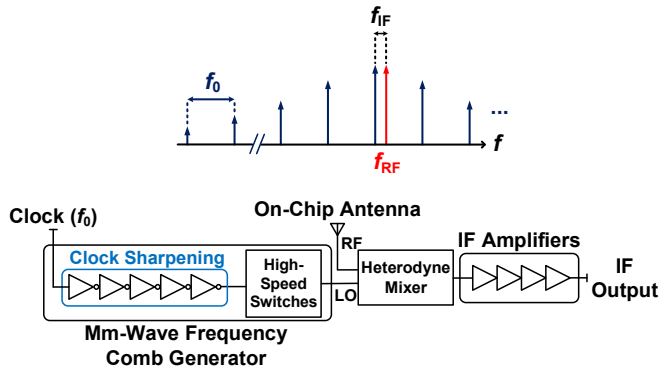


Fig. 1. Concept and architecture of the comb-based millimeter-wave detector chip.

illustrated in Fig. 1. To generate a broadband mm-wave frequency comb on the chip, high-speed transistors are directly switched to produce sharp impulses. Similar to direct digital-to-impulse radiation method in [3], [4], a reference clock is applied to the detector input which sets the repetition frequency and thus, the comb spacing of the frequency comb ( $f_0$ ). Each high-speed switch consists of a transistor loaded with a transmission line, in which the length of the transmission line determines the center frequency of the comb. Since all comb tones are locked to the input clock frequency, this comb can be used as a precise ruler to downconvert any frequency tone within its bandwidth, as it was demonstrated in [5], [6]. Therefore, this frequency comb is used as an LO signal for the heterodyne mixer. The heterodyne mixer is a passive mixer made up of a 65-nm MOS field-effect transistor with 600-nm width. A frequency difference between signals at the gate and source of the transistor ( $f_{IF}$ ) can result in producing the same frequency at the drain of the mixer. Heterodyne detection at higher frequencies is boosted by excited density waves in the FET channel. A single-ended elliptical antenna is implemented as a broadband antenna on the chip to capture received signals. The on-chip antenna feeds the received signal to the detector through a microstrip transmission line. A four-stage amplifier is implemented at the output of the chip to increase the output power. This coherent detector is integrated on a silicon chip using TSMC 65-nm CMOS technology and a picture of the chip assembled on a circuit board is shown in Fig. 2. The area of the miniaturized comb-based detector is 0.56 mm<sup>2</sup> and it consumes 34 mW dc power.

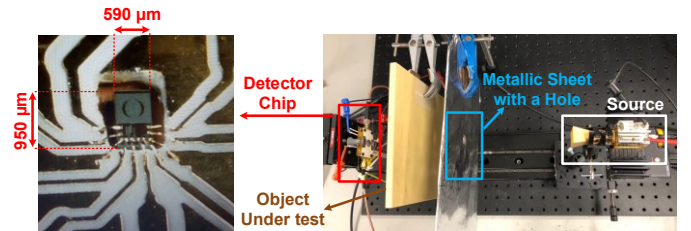


Fig. 2. Photographs of the test board with the mounted chip and the spectroscopy measurement setup.

## III. RESULTS

The described detector chip is mounted in a spectroscopy measurement setup (Fig. 2), in which three continuous-wave sources from 50 GHz to 160 GHz radiate signals toward the detector. Four square sheets with quarter-inch thickness made of Nylon, Polyethylene, Polypropylene, and Polycarbonate are placed between the source and the detector and their effect on the IF signals is measured. A metallic sheet with a small hole is placed behind the object under test to ensure that the signal is only passed through the object and a more accurate measurement is obtained.

For generating signals from 50 to 70 GHz, the +10-dBm output of a Keysight E8257D signal generator is directly connected to a horn antenna through a WR-15 coax to waveguide adapter. To generate frequencies in the W band, a Millitech active multiplier chain is used which multiplies the +3-dBm PSG output frequency by six. The multiplier operates from 75 GHz to 110 GHz and is connected to a horn antenna through a WR-10 coax to waveguide adapter. In the third test, a passive frequency multiplier from Virginia Diodes is connected to the Keysight source to multiply frequencies by three and generate signals above 140 GHz. The comb spacing of the detector is set by a Keysight E4428C signal generator and is set to 2.5 GHz in the first two tests. Comb spacing can be tuned with Hertz-resolution steps to cover specific frequencies in high-precision spectroscopy applications. The radiated frequency tones are set to frequencies that are 50-MHz apart from the comb tones so that the IF frequency is always fixed at 50 MHz. Higher frequency IF tones that are produced by other comb tones are filtered out since the IF amplifier has a cutoff frequency of 2 GHz. The spectrum of the IF output is measured using a Keysight N9030A spectrum analyzer. The objects are placed between the source and the detector and their effect on the IF signals are measured.

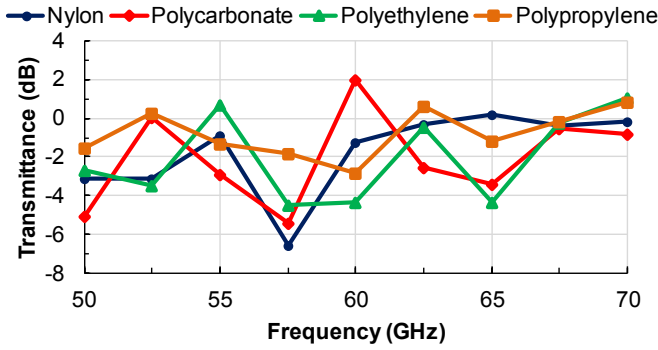


Fig. 3. Measured transmittance through four sheets made of different materials using a 50–70GHz source.

By measuring the IF power at the output of detector before and after placing the objects, transmittance of the objects at each frequency is measured. The measured transmittance of the four tested materials from 50 to 110 GHz are plotted in Fig. 3 and Fig. 4.

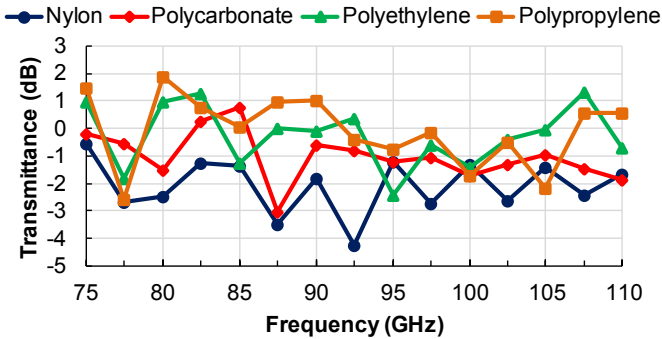


Fig. 4. Measured transmittance through four sheets made of different materials using a 75–110GHz source.

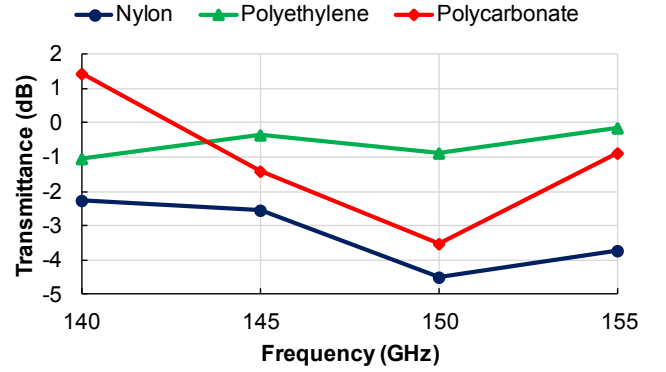


Fig. 5. Measured transmittance through three sheets made of different materials in the 140–155GHz range.

Since the conversion gain of the detector in the third band is lower than first two, the comb spacing needs to be higher than the first two tests to improve the SNR of the IF signal. A higher comb spacing means that the LO power is divided among fewer number of tones, which causes the power of each tone to be increased. As a result, measurements from 140 to 155 GHz were performed with comb spacing of 5 GHz. Transmittance results for this band are reported in Fig. 5.

The behavior of each object over the broad range of frequencies indicates that each object is represented by a unique pattern. Therefore, by performing the same test on numerous more objects, we can categorize their responses based on their materials, thicknesses, shapes, sizes, and other parameters so that an unknown object can be identified based on similarities of its frequency response to each of those categories.

#### IV. SUMMARY

Broadband spectroscopy of four objects made of different materials is demonstrated from 50 GHz to 155 GHz with a fully integrated comb-based mm-wave detector. It is shown that each object exhibits a unique response which can help us in identifying unknown objects using mm-wave frequency combs.

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