A 110 GHz Comb Generator in a 250 nm InP HBT Technology

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***Abstract*— We report a monolithic microwave integrated-circuit (MMIC) comb generator capable of producing a repetitive narrow pulse (7.1 ps pulse duration) with sharp edges (4.2 ps falling time). The circuit was designed in a 250 nm indium phosphide (InP) heterojunction bipolar transistor (HBT) technology using differential pairs. We characterized the output signal with a 110 GHz sampling oscilloscope and de-embedded the band-limited frequency spectrum of the pulse in the circuit reference plane. We measured a pulse duration of 7.1 ps and a peak amplitude of −0.333 V. In the frequency domain, the comb generator provided −48.7 dBm of output power at 110 GHz when the circuit is fed with a 1 GHz input signal.**

***Index Terms*— Comb generator, millimeter-wave, monolithic microwave integrated-circuit (MMIC), on-wafer calibration.**

I. Introduction

ONE of the difficulties in extending the bandwidth of large-signal network analyzers (LSNAs) lies in our inability to perform ultrabroadband phase calibrations. The electrical comb generators that are used to establish an absolute phase relationship between the tones measured at each harmonic-frequency have limited bandwidths. Increasing the bandwidth of the comb generators will consequently increase the measurement bandwidth of the equipment. For instance, a 110 GHz phase reference would allow the characterization of a 28 GHz waveform with three harmonics.

Diverse millimeter-wave comb generator techniques based on nonlinear transmission lines (NLTLs) [1]–[4], step recovery diodes (SRDs) [5]–[7], Josephson junctions (JJs) [8], and split-signal pulse generators [9], [10] have been reported.

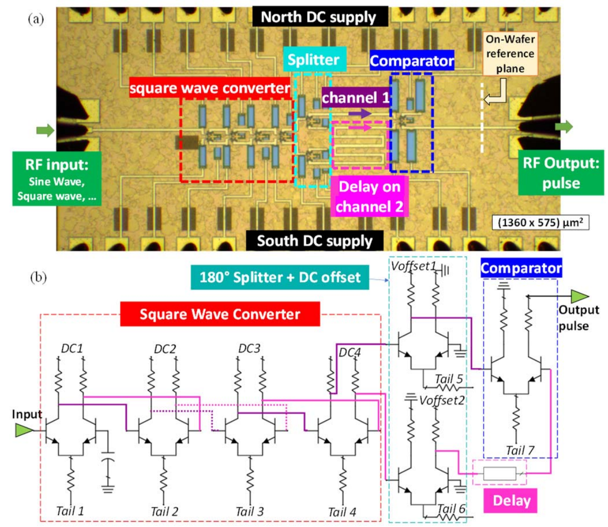

Fig. 1. MMIC comb generator. (a) Photograph. (b) RF schematic.

In this letter, we present a monolithic microwave integrated-circuit (MMIC) differential pulse generator designed in a 250 nm indium phosphide (InP) heterojunction bipolar transistor (HBT) technology. We describe the design methodology in Section II and the time-domain measurement setup in Section III. We finally present the pulse characterization in the time and frequency domains.

II. Comb-Generator Design

We designed the MMIC comb generator using a 250 nm InP HBT process. A full description of the technology may be found in [11]. We simulated the comb generator in ADS,[1] using a transient solver and the foundry's nonlinear transistor model.

We applied the concept of the split-signal pulse generator proposed in [9] to design our circuit. A photograph of the MMIC comb generator is shown in Fig. 1(a) with its RF electrical schematic in Fig. 1(b). The comb generator is composed of a square-wave converter, followed by a 0°/180° splitter, a passive time delay, and a comparator. We designed the active blocks of the circuit with 12 μm-long emitter differential pairs. The current tail is formed using a 200 Ω resistor. Shunt 1.8 pF capacitors and series resistors are used to design the bias tees.

[1]Usage of commercial products herein is for information only; it does not imply recommendation or endorsement by NIST.

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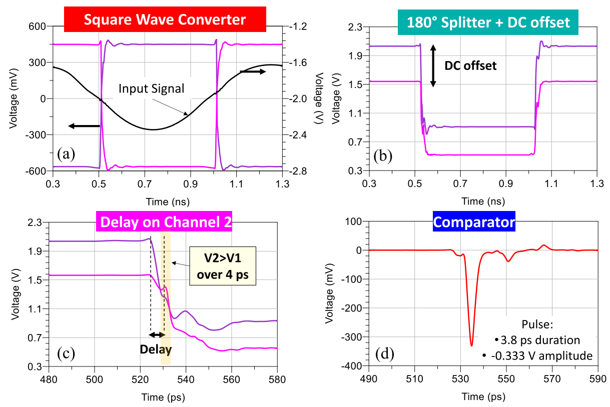

Fig. 2. Simulation of the output voltages of each subcircuit of the comb-generator. (a) Square-wave converter. (b) Out-of-phase splitter. (c) Time delay. (d) Comparator: pulse generator.

The square-wave converter has a single-ended input and a differential output. It converts a periodic signal, such as a sine wave, into two out-of-phase square waves.

Four differential pairs are cascaded to generate two square waves with very sharp edges (<5 ps). A simulation of this subcircuit is presented in Fig. 2(a). Then, we turn the two out-of-phase square waves into two in-phase signals with the 0°/180° splitter, as illustrated in Fig. 2(b). The specific configuration of the two differential pairs allows the generation of two in-phase square waves. At this step, we apply a dc offset on channel 1 to keep the voltage (V1) always higher than the voltage of the second channel (V2). Then, using a transmission line, we add a 3.5 ps delay on channel 2. The voltage of channel 2 becomes consequently higher than the voltage of channel 1 only during a very short amount time (V2 > V1 over only 4 ps), as shown in Fig. 2(c). Finally, we feed these two square waves into a comparator. The current coming from the tail will flow through the second transistor only during the short time when V2 > V1 and consequently generates a narrow pulse. The amplitude and the duration of the pulse are primarily dictated by the delay, the fall time of the square waves, and the dc offset. The resulting output pulse of the circuit is simulated in Fig. 2(d).

III. Measurement Setup

We characterized the comb generator at room temperature with a 110 GHz sampling oscilloscope and de-embedded the pulse on the wafer. All the results were performed with an averaging of 16 measurements. A rigorous calibration method, described in [12]–[14], was applied to calibrate the oscilloscope and move the measurement reference plane to the circuit. This calibration procedure was performed in the frequency domain and was defined in three steps as follows: 1) we decomposed the time-domain signal into its Fourier components (up to 110 GHz) and accounted for the impulse response correction of the oscilloscope; 2) we performed a two-tier calibration to extract the S-parameter block of the adapter (RF pad, RF probe, cables, and bias tee) and de-embedded the complex frequency response, obtained in the previous step, to the circuit reference plane; and 3) we measured the reflection coefficients of the oscilloscope and the comb generator and applied the mismatch correction. Finally, we transformed the Fourier components of the calibrated signal into the time domain to reconstruct the on-wafer waveform. All the steps of this calibration were processed with the Microwave Uncertainty Framework (MUF) software [15].

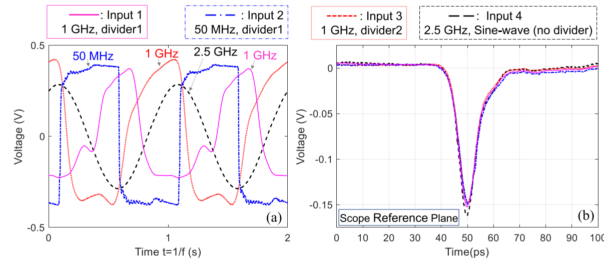

Fig. 3. Comb generator response under different input signals. (a) Input signals and (b) measurements of the pulses at the oscilloscope reference plane.

IV. Comb Generator Characterization

A. Oscilloscope Reference Plane

We first measured the time-domain response of the comb generator with the four input signals illustrated in Fig. 3(a). The objective was to verify that the circuit provides identical pulses under different input excitations and over a wide range of frequency. We successively applied a 2.5 GHz sine wave and three different approximately square waves, generated by frequency dividers, at 50 MHz and 1.0 GHz. The measured responses of the comb generator, plotted in Fig. 3(b), are quasi-identical.

B. On-Wafer Reference Plane

In this section, we applied the calibration process described in Section III to calibrate and transfer the measured pulses in the circuit reference plane. All the following measurements were performed with a 1 GHz square wave excitation [input 3 plotted in red in Fig. 3(a)], but we varied the amplitude of the input signal and bias conditions applied to the circuit.

Fig. 4(a) shows a comparison between the pulse measured in the oscilloscope reference plane and the calibrated pulse de-embedded on chip. The peak amplitude of the on-wafer pulse reaches a voltage of -0.251 V (at bias 1). The waveform artifacts (sinc wiggles) observed on each side of the pulse are the results of the 110 GHz truncation that we applied during the Fourier transform. Then, we applied different (OFF-chip) attenuations at the input of the comb generator to determine the minimum input amplitude required by the circuit. We found that the comb generator requires an amplitude of at least 30 mVpp to correctly operate. This amplitude corresponds to an attenuation of 30 dB of the original input-signal amplitude (0.880 Vpp). These results are plotted in Fig. 4(b). We also evaluated the measurement repeatability of the pulse over time, as shown in Fig. 4(c). We realized six measurements of the pulse (1 min interval) and measured it a final time after 45 min. We observed minor differences. Finally, we varied the bias point of the differential pairs to optimize the pulse duration and amplitude. The results are presented in Fig. 4(d). We first optimized the bias points (bias 2) to obtain the sharpest and narrowest pulse. The pulse duration is defined at

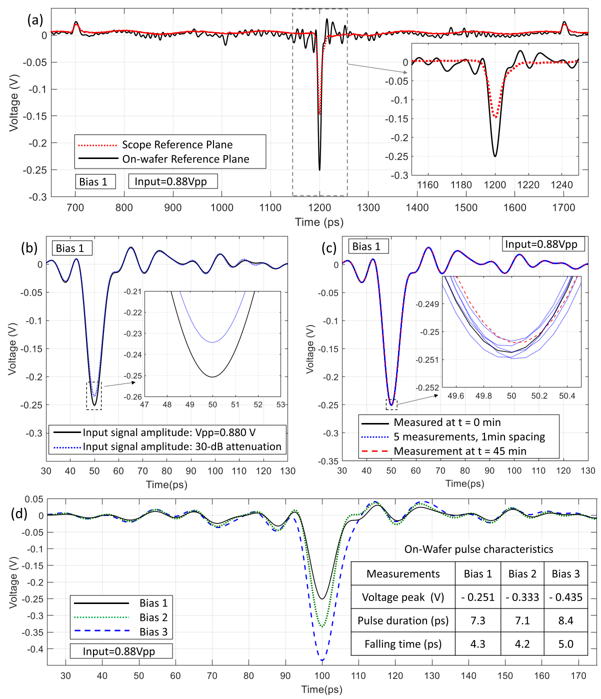

Fig. 4. On-wafer comb generator measurement results in the time domain. (a) Comparison between a pulse measured in the oscilloscope reference plane and a calibrated pulse transferred on-wafer. (b) Pulse measurements under two different input-signal amplitudes. (c) Pulse measurement repeatability. (d) Pulse measurements under different bias points.

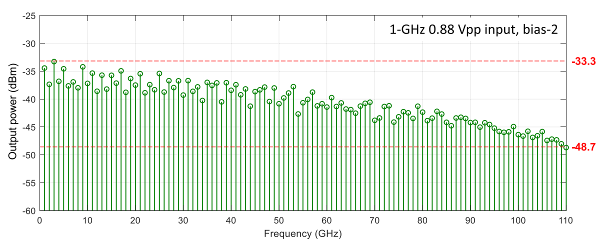

Fig. 5. Amplitude of the frequency spectrum of the on-wafer calibrated pulse (bias 2).

50% of the pulse amplitude, and the falling time corresponds to the time required by the circuit to go from 10% to 90% of the pulse amplitude. We measured a pulse duration of 7.1 ps, a falling time of 4.2 ps, and a peak amplitude of −0.333 V. Then, we tuned the dc supplies and targeted the maximum pulse amplitude. Although we measured a larger peak voltage (−0.435 V with bias 3), the time characteristics of the pulse increased, reducing the frequency bandwidth. The comb-generator bias conditions change the characteristic of the generated pulse, but the dc bias (dc offsets + current tails) of two differential pairs that form the splitter are the most critical and must be carefully adjusted to obtain the best performance.

The pulse (bias 2) presented in Fig. 4(d) offers the widest bandwidth in the frequency domain. We plot the band-limited frequency spectrum of the calibrated pulse in Fig. 5. Although the energy of the harmonics slightly decreases with increasing frequency, we measured a reasonable amount of power at 110 GHz (−48.7 dBm), which is above the power easily detected by nonlinear vector network analyzers (−100 dBm).

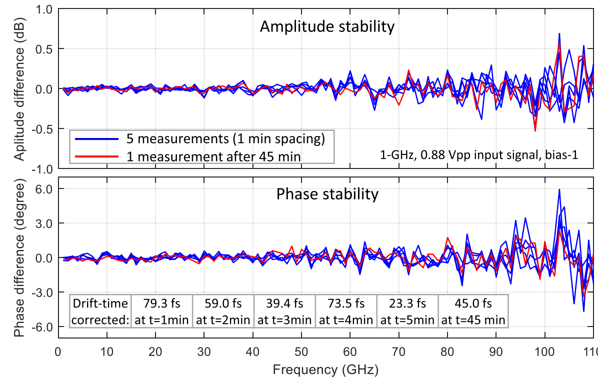

Fig. 6. Amplitude and phase stability of the frequency spectrum over time of the on-wafer comb generator (bias 1).

TABLE I

ON-WAFER CHARACTERISTICS OF THE COMB GENERATOR

Input Specifications	
Frequency range of operation:	≥ 50 MHz
Periodic input signals:	Sine, square,…
Voltage input signal: (>30 dB operation range)	> 30 mVpp
Measured* Output Characteristics	
Maximum pulse peak amplitude:	-0.435 V
Minimum pulse duration:	7.1 ps
Minimum falling time:	4.2 ps
Maximum amplitude error of the spectrum:	0.69 dB
Maximum phase error of the spectrum:	5.93 °
Maximum power at 110 GHz: (1 GHz spacing):	-48.7 dBm

* *Time domain measurements are limited to the bandwidth of the oscilloscope (110 GHz)*

Finally, we studied the amplitude and phase stability of the frequency spectrum of the comb generator. We converted the data acquired over time [presented in Fig. 4(c)] into the frequency domain and plotted the amplitude and phase difference on Fig. 6. The first measurement taken a $t = 0$ min is used as the reference. The drift over the span of an hour is less than 100 fs and has been corrected. We obtained an excellent amplitude and phase stability, with maximum amplitude and phase error of 0.69 dB and 5.63°, respectively, at 110 GHz.

The main characteristics of the proposed comb generator are summarized in Table I. Note that we measure only a band-limited frequency spectrum of the pulse. The bandwidth of the comb generator, defined by frequency at which the comb-generator output first falls below the noise floor of the output signal, is well above 110 GHz and appears to exceed the 67 GHz bandwidth of commercial split-signal pulse generators [10]. Compared with NLTL [3], [4], SRD [6], [7], and JJ [8] comb generators previously published, we also demonstrate a wider bandwidth, a finer frequency spacing, and an output signal insensitive to a variety of input excitations. We will pursue our investigation to determine the exact cutoff frequency of the proposed comb generator.

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