Electro-Optically Derived Arbitrary Millimeter-Wave Sources with 100 GHz of Bandwidth

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Abstract: We demonstrate fine phase and amplitude control of millimeter-waves, measured on-wafer using an electro-optic frequency comb, programmable spectral filter, and uni-traveling carrier photodiode. We then synthesize arbitrary waveforms with 100 GHz of bandwidth and +12.7 dBm amplitude.

Integrated circuits in communication electronics require nonlinear characterization with large input amplitude (e.g., greater than 0 dBm) waveforms and modulated waveforms to optimize performance and energy efficiency. Often time-domain digital-to-analog converters can generate these desired waveforms, but circuits for new 5G millimeter-wave bands [1] will require new precision waveform generators for high frequency circuit characterization. Optical frequency combs (OFCs) can easily span several THz of instantaneous bandwidth with thousands of synchronized comb lines, making them an ideal starting point for waveform generation [2]. Coupled with uni-traveling carrier (UTC) photodiodes [3,4] capable of high-power handling and high linearity, stabilized OFCs have produced millimeter waves with the lowest phase noise and best frequency stability measured to date [5,6]. Here we demonstrate precise phase (25 millirad stepped) and amplitude (0.1 dB stepped) control of millimeter-waves at 24.8 GHz, 49.6 GHz, 74.4 GHz, and 99.2 GHz by controlling the optical spectrum of an OFC, and apply this to generation of arbitrary repetitive waveforms with 100 GHz of bandwidth and greater than 450 mV amplitude.

The system begins with an electro-optic frequency comb, driven with a commercial synthesizer at 24.8 GHz. The resulting optical comb has 24.8 GHz tooth spacing and more than 1 THz of bandwidth. An erbium-doped fiber amplifier (EDFA) provides coarse amplitude control before (⋄ in Fig. 1) or after († in Fig. 1) a commercial programmable spectral filter. The main output from the filter illuminates a photodiode chip connected through a wafer probe to a 110 GHz vector network analyzer (VNA). A second output from the filter selects a second pair of comb lines with tunable spacing to act as a phase reference when detected by a packaged 100 GHz photodiode. The 24.8 GHz fundamental frequency was chosen to place the fifth harmonic at 124 GHz, near the edge of the measurement bandwidth of the VNA. Unfortunately, it was not possible to calibrate the data above 110 GHz, so we only include measurements at 24.8 GHz, 49.6 GHz, 74.4 GHz, and 99.2 GHz.

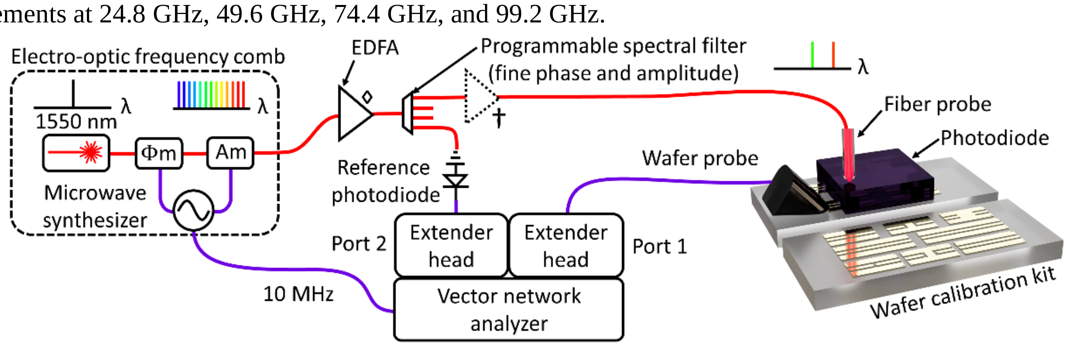

Fig. 1. Schematic diagram of the millimeter-wave source with phase and amplitude control. An electro-optic frequency comb is amplified by an EDFA and filtered by a programmable spectral filter. Two or more comb lines are filtered and phase- and amplitude-shifted to generate single- or multi-tone programmable waveforms. On-wafer measurement with a vector network analyzer lets us characterize the system performance at the edge of the photodiode chip.

The photodiode is a modified UTC (MUTC) design with 8 μm diameter; the device is flip-chip bonded onto an aluminum nitride substrate for heat sinking with gold coplanar waveguide (CPW) contacts. To determine the power performance and linear operating range of the MUTC photodiode, we performed a two-tier microwave scattering (S-) parameter and power calibration. A coaxial 1.0 mm connectorized calibration and power calibration let us convert voltage wave parameters measured inside the network analyzer to absolute millimeter-wave power (up to 110 GHz) at the coaxial reference plane. An on-wafer calibration with 50 Ω reference impedance lets us translate the voltage wave parameters to the on-wafer reference plane at the wafer probe tip. In this way, we were able to measure almost ideal millimeter-wave power conversion per dc photocurrent, depicted in Fig. 2(a). At 49.6 GHz, the photodiode reached peak power at 31 mA and 12.7 dBm output power, 1.2 dB below the ideal. At 99.2 GHz, the photodiode reached peak power at 25 mA and 7.3 dBm, 4.7 dB below the ideal. For programmable waveform generation, we operated the diode in the linear region (below the onset of bandwidth enhancement at high photocurrents) below 10 mA of photocurrent.

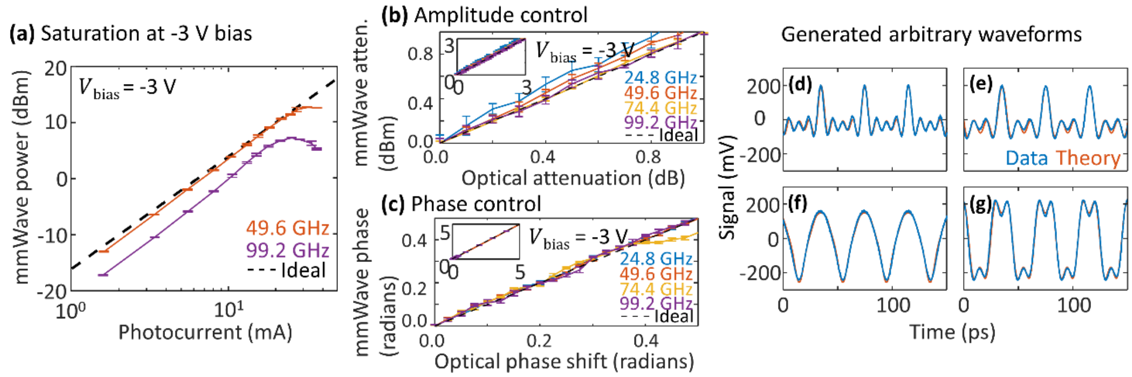

Fig. 2. Photodiode performance and millimeter-wave phase and amplitude control via control of the optical spectrum. Optical attenuation (b) in 0.1 dB steps and optical phase shift (c) in 25 millirad steps of one of the comb lines lead to nearly ideal millimeter-wave attenuation and phase shift. This phase and amplitude control was also applied to generating arbitrary time domain waveforms: (d) sinc pulses with 100 GHz of bandwidth, (e) sinc pulses with 75 GHz of bandwidth, (f) rectified sine waves, and (g) square waves.

In Fig. 2(b,c), we demonstrate linear phase and amplitude control of a single millimeter-wave frequency by filtering a pair of comb lines with desired frequency spacing and optically phase- and amplitude-shifting one of the comb lines. The response to the filter is extremely linear with only two notable issues. For closely spaced comb lines (24.8 GHz and 49.6 GHz) there appears to be some crosstalk between the adjacent bands causing a higher attenuation slope. Secondly, there appears to be a random walk in some of the phase shift data, due most likely to differential path length drift and the fact that the electro-optic comb bias was not actively controlled for this measurement.

In Fig. 2(d-g), we apply these findings to generation of arbitrary repetitive waveforms measured by a 100 GHz sampling oscilloscope. In the spectral filter, a phase profile to compress the comb's optical autocorrelation was applied along with an equalization to the EDFA gain to generate a flat amplitude and zero-phase optical spectrum. Phase and amplitude profiles were then calculated for the central five comb lines (four pairwise spacings) to generate desired waveforms, taking into account the measured optical impulse response of the photodiode and electronic path leading up to the oscilloscope sampler. The predicted (denoted "Theory") and measured (denoted "Data") waveforms show excellent agreement. For all four waveforms, the dc photocurrent was set at 7.5 mA to avoid saturating the oscilloscope, although the photodiode can easily generate higher-voltage waveforms, especially if the nonlinear response is taken into account. The noise performance also indicates that the electro-optic comb generation and spectral filtering are suitable for extending beyond 100 GHz with UTC photodiodes designed for THz generation [3,7].

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