Electro-Optic Imaging Millimeter-Wave Propagation On-Wafer

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Abstract: We demonstrate an electro-optic imaging system for millimeter-waves propagating along a coplanar waveguide. Using dual optical frequency combs and a polarization resolved microscope, we image signals with bandwidth >100 GHz and >48 dB dynamic range.

Emerging integrated circuits operating in new millimeter-wave (mmWave) bands for 6G and beyond [1] require new waveform generators [2] and receivers for high-frequency circuit characterization. Characterizing circuits' time-domain, nonlinear harmonic, and intermodulation responses is especially important for optimizing energy efficiency and stability. Electro-optic sampling of a photodiode's impulse response is a well-established technique for calibrating oscilloscopes and phase references up to 110 GHz [3]. Large signal network analysis (LSNA) can theoretically extend time-domain measurements well beyond 110 GHz, but this approach practically requires a suite of banded frequency instruments and commercially unavailable electronic comb generators [4]. Here, we extend electro-optic sampling to acquire *spatio*-temporal images of mmWaves along the length of a coplanar waveguide (CPW). We image the electro-optic response at 70 locations in parallel to observe voltage standing waves up to >100 GHz, enabling LSNA on-wafer. The current measurement samples up to 500 GHz (with system resolution >1 THz), which is well beyond the bandwidth of the photodiode signal source.

The experimental system (Fig. 1) begins with two electro-optic frequency combs driven by commercial radio frequency synthesizers set to repetition frequencies $f_{rep,1}$ = 25 GHz and $f_{rep,2}$ = 25 GHz + 210 Hz. Both combs are centered at 1550 nm and tuned for greater than 1.3 THz of 3 dB optical bandwidth. Programmable spectral filters compress and bandpass-filter both combs to have approximately Gaussian spectra and 670 fs FWHM pulse width, determined by intensity autocorrelation. Comb 1 acts as the sampling beam; comb 2 illuminates a photodiode to create mmWave test signals with greater than 100 GHz of bandwidth.

In the illumination path, comb 1 is projected as a line of spots onto a gold coplanar waveguide (CPW) fabricated on a Lithium tantalate ($LiTaO_3$) wafer. A Powell lens and scan lens with a focal length (FL) of 50 mm shape the beam from comb 1 to a uniform line ("top hat" beam) incident on a linear pinhole array. The illumination tube lens (FL = 200 mm) and 2.5× near-infrared (NIR), 0.1 numerical aperture (NA), microscope objective image the pinhole array onto one of the gaps of the CPW. Pulses from comb 2 illuminate a 100 GHz, 1.0 mm coaxial connectorized photodiode. The repetitive impulse response of the photodiode travels through a 110 GHz bias-T and ground-signal-ground microwave wafer probe, which contacts the landing pads of the CPW. The sampling beam passing through the tantalate wafer experiences a small polarization rotation due to the Pockels effect induced by the electric field applied between the signal and ground of the CPW.

In the collection path, a matching 2.5× NIR microscope objective collects the light from the top side of the wafer.

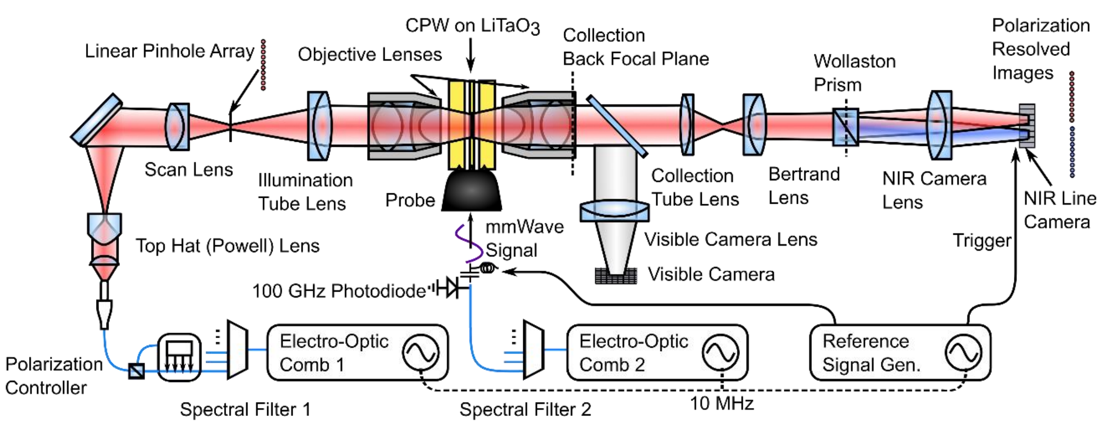

Fig. 1. Schematic diagram of the electro-optic imaging system. Electro-Optic Frequency Comb 1 ($f_{rep,1}$ = 25 GHz) projects a linear spot array through the illumination path onto one of the gaps of a coplanar waveguide (CPW) on a Lithium tantalate substrate. The collection path images orthogonal polarization states onto two halves of a near-infrared line camera. Electro-Optic Frequency Comb 2 ($f_{rep,1}$ = 25 GHz + 210 Hz) illuminates a photodiode that probes the CPW to launch test voltage waveforms with greater than 100 GHz of bandwidth.

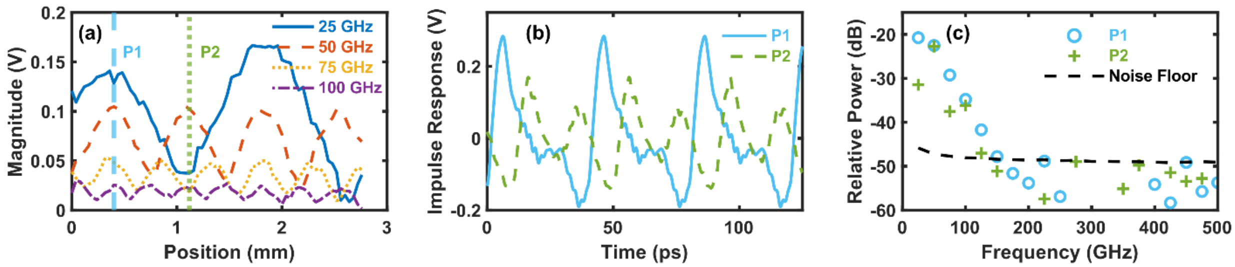

Fig. 2. Measurements of voltage standing waves along the CPW. (a) Magnitude of the voltage waves at 25 GHz, 50 GHz, 75 GHz, and 100 GHz versus sampling position (40 µm pitch) along the CPW. (b) Reconstructed time domain waveforms at locations marked P1 and P2, showing the effect of spatially dependent impedance along the CPW terminated by an open circuit. (c) Corresponding frequency content and estimated noise floor at P1 and P2.

The collection tube lens (FL = 200 mm) and Bertrand lens (FL = 100 mm) act as a bi-telecentric relay to image the back focal plane of the collection objective into a Wollaston prism (7.3 degree splitting angle). Finally, a high-resolution camera lens (FL = 50 mm) images the vertical and horizontal polarizations to different halves of the sensor in an InGaAs NIR line camera. To ensure long-term stability of the polarization measurement, an automatic polarization controller restores comb 1 to linear polarization before the launch into free space. Combinations of quarter-wave and half-wave retarders (not depicted in Fig. 1) before the scan lens and Wollaston prism set the desired 45˚ linear polarization at the CPW and the prism.

To optimize imaging performance, we carefully selected the line camera sensor to achieve maximum shot-noise-limited signal-to-noise ratio. The pinhole array simplifies registration of the two polarization images. The current pinhole array offers 70 diffraction limited spots (NA = 0.1) with a 40 µm pitch along the CPW gap (120 spots would cover the full pixel array). This is sufficient for Nyquist imaging (>2 spots per electrical wavelength on-wafer) of mmWaves beyond 850 GHz, but the system resolution can easily exceed 1 THz with a finer spot pitch or lower dielectric constant electro-optic substrate. For the present experiment, we set the offset frequency $f_{rep,2}$ - $f_{rep,1}$ to fit 20 harmonics (up to 500 GHz) within the 9.6 kHz line rate, limited by the camera USB3 interface. The reference signal generator provides the trigger signal to the line camera as well as a low-frequency calibration signal (500 Hz sine wave with 1.4 V peak amplitude) independent of the photodiode, connected through the DC port of the bias-T to the CPW. The low-frequency calibration signal should be constant along the CPW that is terminated with an open circuit. Therefore, we use the demodulated reference amplitude and phase to normalize the binned pixel data.

By sampling multiple positions along the CPW, amplitude and phase of all harmonics at multiple mmWave reference planes can be measured simultaneously, revealing forward and backward traveling waves [5]. Figure 2 depicts measurements of standing waves generated by the impulse response of the photodiode traveling forward and backward along the CPW. The 2.8 mm field of view is approximately centered along the 8.6 mm length of the CPW. The open circuit that terminates the CPW reflects the input signal almost completely. Figure 2(a) depicts the amplitude of the measured voltage at 25 GHz, 50 GHz, 75 GHz, and 100 GHz versus sampling position along the CPW. Figure 2(b) depicts the reconstructed time domain waveforms with full frequency content at two locations, marked P1 and P2 at 0.4 mm and 1.12 mm, respectively. At P1, all frequencies are strongly reflected and in phase so the P1 impulse response in Fig. 2(b) appears as it would in an oscilloscope with a matched load, but with higher voltage due to the forward and backward traveling waves. At P2, 25 GHz and 75 GHz are attenuated by deconstructive interference and the impulse response computed without performing an impedance correction shows significant distortion. Figure 2(c) depicts the frequency power content of Fig. 2(b) normalized to the reference signal. We estimated the noise level from the peak values of the Fourier transform within a ± 2 Hz bandwidth around the demodulated frequencies (not shown) and found that with a 1745 s integration time, the system achieves greater than 48 dB dynamic range between the reference signal and the peak noise level.

In conclusion, we demonstrated a new kind of electro-optic sampling system that measures spatio-temporal images of mmWaves traveling on-wafer. Spatio-temporal imaging opens the possibility for large signal network analysis of integrated circuits on-wafer at frequencies from a few GHz to greater than 1 THz.

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