

An On-Chip Frequency-Domain Submillimeter-Wave Spectrometer

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Sponsorship

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Because of the frequency limitation of semiconductor electronic devices, measurement instruments such as network analyzers can operate only below approximately 100 GHz. Thus, even if ultrahigh-frequency HBTs can be developed, they can only be directly measured up to 100 GHz, with higher-frequency performance extrapolated according to certain frequency roll-off models. Clearly, such an extrapolated measurement will not be applicable to measuring high-frequency resonance such as that shown in Figure 15. It will be very useful to develop on-chip systems that can characterize device performance up to THz frequencies. A promising component for such systems is ultrafast photoconductive switches made of Low-Temperature-Grown (LTG) GaAs materials. When pumped with two coherent laser beams, such switches can generate and detect photocurrent with a modulation frequency beyond one THz.

Furthermore, photoconductive emitters and receivers are attractive as components of sub-millimeter-wave spectroscopy systems because of their tunability, compactness and ability to be monolithically integrated with antennas, transmission lines and microelectronic devices. Such systems can be classified either as time-domain or frequency-domain systems. Time-domain systems, which contain a photoconductive pulse emitter and sampler excited by a mode-locked laser, are the most investigated. They have been used for free-space characterization of semiconductor materials, and on-chip characterization of ultrafast devices and circuits with 2.7 ps time resolution. The frequency resolution is the inverse of the time span over which the propagating pulse is sampled. This span is determined by the length of an optical delay line, which usually results in a frequency resolution broader than 1 GHz.

The emitter and receiver of a frequency-domain spectrometer will be pumped by two coherent cw laser beams with frequencies ω_1 and ω_2 , instead of short laser pulses. If the response time is sufficiently fast, the emitter switch will generate an ac photocurrent with a frequency

$|\omega_2 - \omega_1|$, which can easily exceed 1 THz. Illuminated by the same two laser beams with a controlled delay, the receiver switch can be used to perform a homodyne detection of the ac photocurrent generated from the emitter. In combination with high-frequency transmission lines, they can form on-chip spectrometers with THz bandwidths. Figure 15 illustrates a schematic of such a spectrometer that can be used to characterize common-emitter performance of high-frequency HBTs.

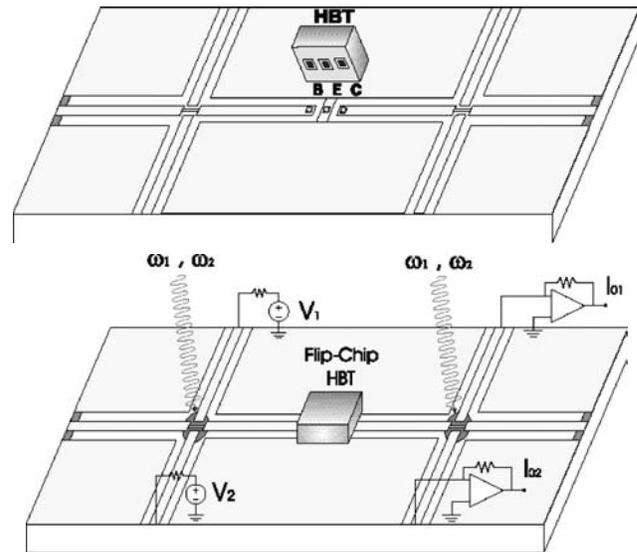


Fig. 12: Schematic of a on-chip spectrometer that uses ultrafast photoconductive switches to generate and detect ultrahigh-frequency signals.

Because of the broad bandwidth (>1 THz) and a high frequency resolution (better than 1 MHz), such a spectrometer is also adequate for molecular line spectroscopy. In combination with microchambers, the spectrometer can be part of a microfluidic, "lab on a chip"-type circuit, which can be used as on-chip sensors for chemical and biological agents. As the first step in the development of an on-chip frequency-domain spectrometer, we have investigated the performance of an on-chip transceiver containing only uninterrupted coplanar waveguides (CPWs).

Our circuit, shown in Figure 16(a), has a biased pump photoconductor and an unbiased probe photoconductor connected by a main CPW, and other parasitic CPWs which provide DC electrical contact to the photoconductors. As illustrated in Figure 16(a), we excited propagating electromagnetic waves at the pump by illuminating the pump photoconductor with two overlapping diode laser beams with a difference frequency $f = \omega_2 - \omega_1$. We performed homodyne detection of those waves by illuminating the probe with a delayed portion of the same laser beams. The relative delay between the pump and probe beams is the phase Φ . The output DC current I_{O1} should vary sinusoidally with Φ , $I_{O1}(\Phi) = I_0 \cos(\Phi + \delta)$, because of the homodyne detection performed at the probe photoconductor. The argument of cosine contains two terms: the phase Φ , which is due only to the path lengths of the pump and probe beams; and the phase δ , which describes the response of the circuit and any device or specimen inserted in it. For example, δ may be non-zero because of the dispersion of the CPWs or circuit resonance. Our aim was to measure I_0 and δ as functions of f . Together, I_0 and δ contain all the information necessary for coherent spectroscopy.

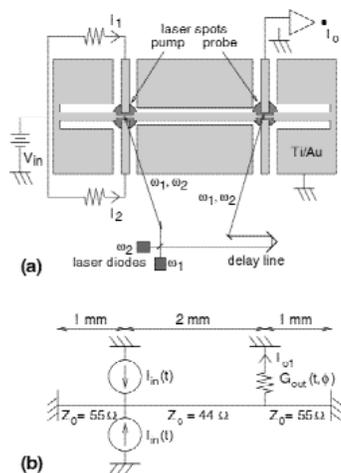


Fig. 16: (a): Diagram of the experimental circuit, showing its electrical bias and optical input. (b) Microwave circuit model of the experimental circuit.

We fit the measured spectra to a model based on the circuit shown in Figure 16(b). The two active regions of the pump photoconductor are modeled as current sources. Similarly, the single utilized active region of the probe photoconductor is modeled as the time-varying conductance. We assume that the CPWs have a propagation constant $\Gamma = \alpha(f) + j2\pi f/v_p$, where $\alpha(f)$ is the attenuation constant to be fit to the data, and v_p is the phase velocity of a coplanar transmission line on a semi-infinite GaAs substrate. We use standard microwave circuit analysis to calculate I_{O1} , the Φ -dependent DC current generated at the probe.

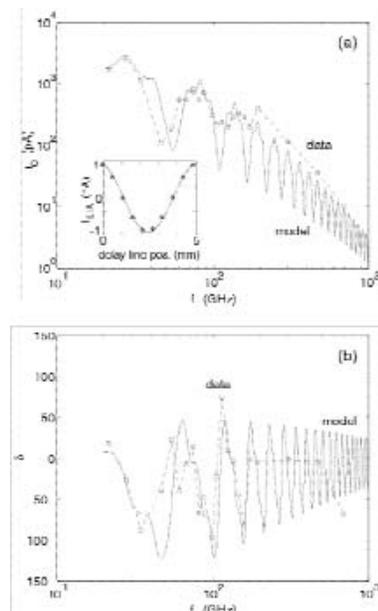


Fig. 17: Measured data and model of the amplitude and phase spectra (a) $I_O(f)$ and (b) $\delta(f)$. Inset: output of lock-in amplifier vs. delay line position at $f = 27.9$ GHz, compared to a best-fit sinusoid.

Our model was fit to the data with reasonable fitting parameters. As shown in Figure 17c, the agreement between the model and the measured results is quite good, validating the microwave-circuit analysis of our on-chip submillimeter-wave transceiver.