Broadband Millimeter-Wave GaAs Transmitters and Receivers Using Planar Bow-Tie Antennas

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Abstract

We report broadband monolithic transmitters and receivers ICs for mm-wave electromagnetic measurements. The ICs use non-linear transmission lines (NLTL) and sampling circuits as picosecond pulse generators and detectors. The pulses are radiated and received by planar monolithic bow-tie antennas, collimated with silicon substrate lenses and off-axis parabolic reflectors. Through Fourier transformation of the received pulse, 30-250 GHz free space gain-frequency measurements are demonstrated with ≈ 0.17 dB accuracy, RMS.

Introduction

For mm-wave and sub-mm wave gain-frequency measurements, convenient, broadband power sources and detectors have been required for some time. Measurement systems based upon waveguide components (harmonic mixers, frequency multipliers, and horn antennas)[1] have played a dominant role, but each component has narrowband frequency coverage (1.5:1). To measure over a broad bandwidth, many waveguide systems must be used, which is both inconvenient and very expensive. In addition, above 100 GHz it is difficult and expensive to machine the small waveguides and difficult to attain efficient device-waveguide coupling. Broadband monolithic mm-wave ICs address these difficulties.

Several groups have reported superconductor devices such as SIS (Superconductor-Insulator-Superconductor) detectors[2-4] or oscillators[5] for mm-wave measurement or for radio astronomy. Popular devices based on niobium technology (e.g., Nb/AlO$_X$/Nb junctions) must be cooled to liquid helium temperature, so a large and expensive cooling system is required. Additionally, due to the very low impedance of superconducting devices (≈ 0.1 Ω), impedance matching to a 50 Ω system is difficult.

Antenna-coupled picosecond photoconductors have also been used to generate and detect picosecond radiated electromagnetic pulses. Though Fourier analysis of the received signals, several groups have recently demonstrated broadband spectroscopy (≈ 50 GHz-1.5 THz) [6-8]. Such systems require expensive and complex mode-locked lasers (≈ $150,000) to excite the photoconductors, and the radiated power is extremely small.

As with the photoconductive systems, our system for mm-wave measurements radiates and detects picosecond pulses and obtains frequency information through Fourier transformation. Our system uses solid-state monolithic devices, NLTLs and sampling circuits for pulse generation and detection[9-11]. With the NLTLs, we have several advantages. First, the system has fewer components and is very compact without the laser or its optics. Second, there is substantially more radiated power than the photoconductive system. Third, since the NLTL is driven by a microwave synthesizer and the NLTL input frequency can be varied by as much as one octave, the system can easily be tuned to any desired mm-wave harmonic frequency. Finally, the transmitters and receivers are inexpensive components fabricated on GaAs with a 5 mask process at 3 μm device geometries. No cooling system is required for GaAs ICs as with the superconducting devices.

Here we will describe the system, especially the broadband bow-tie antenna and its optics. We have demonstrated the system performance by spectroscopic measurement of a thin alumina substrate with accuracy of 0.17 dB RMS and reproducibility better than 0.3 dB from 30 to 250 GHz.

NLTLs & sampling circuits

The NLTL is a ladder network of high impedance transmission line sections periodically loaded with reversed biased monolithic Schottky diodes serving as voltage-variable capacitors[9]. The resulting voltage-variation in wave propagation velocity results in the compression of negative-going wavefronts and the formation of picosecond shock-waves. The NLTL converts an input 7 - 14 GHz sine wave to a sawtooth waveform. In on-wafer measurements, ≈ 1.5 ps falltime and ≈ 5 V peak to peak voltage swing has been attained. NLTL-gated sampling circuits attained similar risetime. Such devices allow generation and detection of transient signal with ≈ 250 GHz bandwidth. The transmitter NLTL is typically driven by a 10 GHz + 100 Hz sinusoidal wave from a microwave synthesizer. This NLTL drives an on-wafer bow-tie antenna. The receiver consists of an NLTL-gated sampling circuit integrated with a bow-tie antenna. The NLTL which generates the sampler's strobe pulse is typically driven by a 10 GHz sinusoidal waveform from a second synthesizer. The resulting sampled 100 Hz IF signal is observed on a standard oscilloscope.

Antenna and quasi-optical system

In the case of a planar antenna on a dielectric substrate, most of the power is radiated into the substrate, and is trapped. This causes standing waves and resulting resonances within the GaAs substrate ($\varepsilon r = 13$). To avoid this, hyper-hemispherical substrate lenses are used with the bow-tie antennas[12,13].

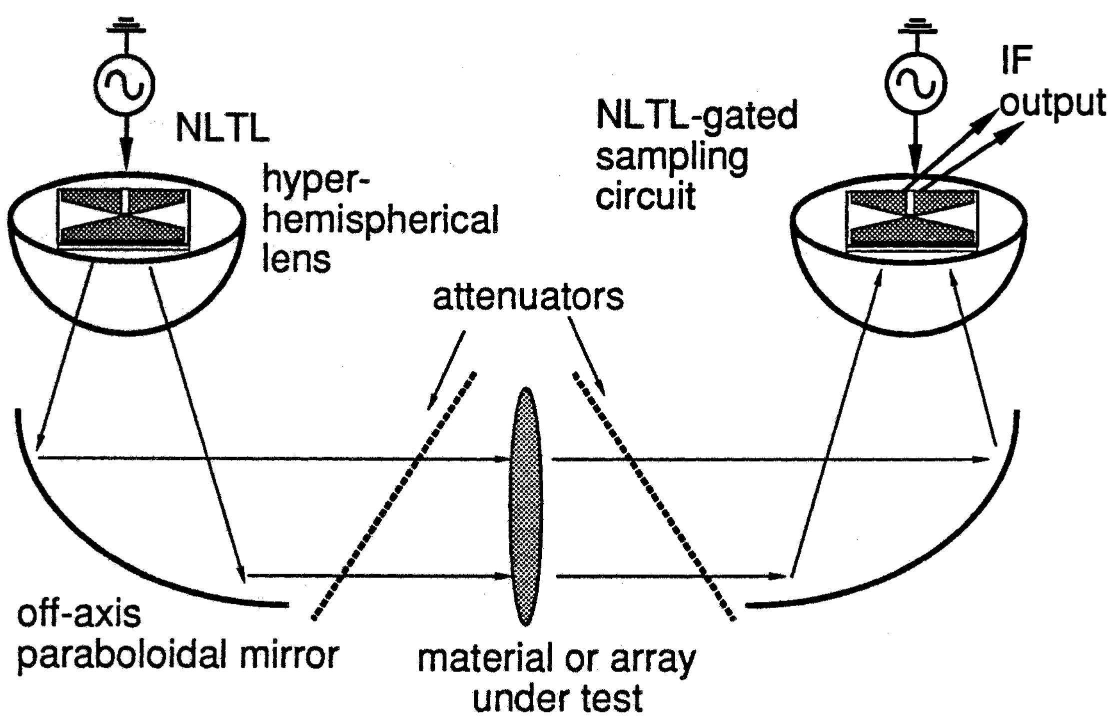

Figure 1: Measurement system schematic diagram (left: transmitter, right: receiver)

The output of the transmitter NLTL is connected by a coplanar waveguide (CPW) feed line to the feedpoint of the bow-tie antenna. This structure also serves as a balun. Sawtooth waves generated by the NLTL are radiated from the antenna. The bow-tie antenna is scale-invariant and has frequency-independent radiation impedance and frequency-independent far-field radiation patterns as long as its linear dimensions are larger than a free space wavelength. The antenna thus acts as a high pass filter, with the 2 mm length resulting in a ≈ 35 GHz low-frequency cut-off[14]. The 55 µm total width of the CPW feedline defines a ≈ 1.3 THz upper frequency limit for the antenna.

The radiation is extracted through a silicon (εr= 11.8, 16 mm diameter) hyper-hemispherical substrate lens on the back side of the IC. Matching of the IC and lens dielectric constants is very important. For example, a sapphire lens (εr= 9.9) causes standing waves in GaAs substrate due to the discrepancy in εr. This results in substantial resonances at 60 GHz, 120 GHz and 180 GHz. Compared to hemispherical lenses, hyper-hemispherical lenses improve the poor numerical aperture of the bow-tie antennas, and provide defocusing of the parasitic reflections arising at the lens-air interface. In contrast, hemispherical lenses exhibit strong spherical-mode resonances. The radiated beam is collimated with off-axis parabolic mirrors, and is focused on the receiver through similar optics. The antenna system loss, including substrate lenses absorption, coupling loss between the antenna and the lens etc., is ≈ -20 dB as determined by 10 MHz - 40 GHz network analysis[14].

Metal surfaces surrounding the experimental apparatus are covered with microwave absorber (Emerson & Cuming, FGM-40) to suppress reflections. Additionally, imaging the transmitter antenna onto the receiver produces a resonant cavity because of reflections at the air-lens and lens-antenna interfaces. To obtain accurate gain-frequency measurements, these resonances are suppressed by placing ≈ 5 dB thin-film metal attenuators on both sides of the sample under test.

Device Fabrication

The circuits were fabricated on GaAs semi-insulating substrates with a five mask process at 3 µm design rules. Schottky diodes are formed on GaAs with a 425-nm-thick exponentially graded N^- active layer with a 2×10^{17} cm^{-3} surface doping and 225 nm exponential grading constant. Beneath the N^- layer, a buried 1 µm-thick N^+ layer (6×10^{18} cm^{-3}) provides the diode cathode connection. Ohmic contacts to the N^+ later (the diode cathode connections) are formed by a 0.5 µm recess etch to the N^+ layer, a self-aligned AuGe/Ni/Au liftoff, and subsequent alloying. Proton implantation (masked by 1.6 µm gold on 1.1 µm polyimide) provides isolation between diodes and defines Schottky contact areas. The transmission line sections are implemented in CPW, formed with a 1.1 µm Ti/Pt/Au liftoff; Schottky contacts result where this liftoff intersects unimplanted regions. With two additional mask steps, air-bridge crossovers are formed.

Results

The received signal (Fig. 2) shows that the sawtooth waveform has changed to a pulse train with initial fast rise and a decay time set by the antenna system's low-frequency cut-off. The peak-peak amplitude is 167 mV, and the pulse risetime is 2.6 ps as limited by the speed of sampling circuits, the NLTL, and the antenna system.

Because the far-field radiation pattern is frequency-independent, the antenna effective aperture size is proportional to λ^2. Consequently, misalignment selectively attenuates high-frequency components and limits the system bandwidth. With poor alignment, the pulse risetime degrades due to the reduced bandwidth.

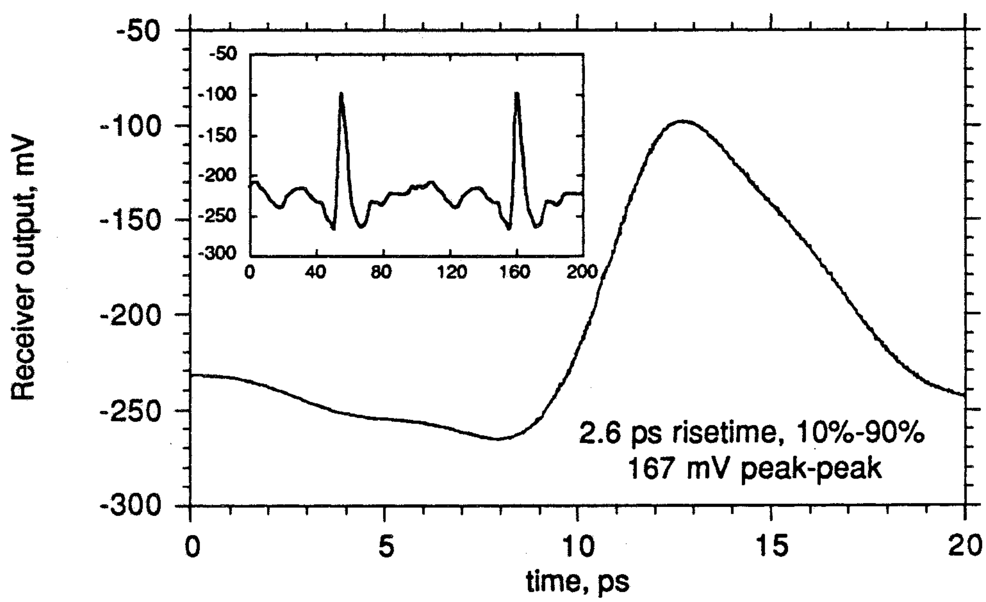

Figure 2: Received waveform.

To demonstrate the system accuracy, we measured the insertion loss of a 254 μm alumina substrate (εr= 9.9). From 30 to 250 GHz the measurement values correspond well to theory. (Fig.3) With three subsequent measurements, the accuracy attained was 0.17 dB RMS, and the reproducibility was better than 0.3 dB.

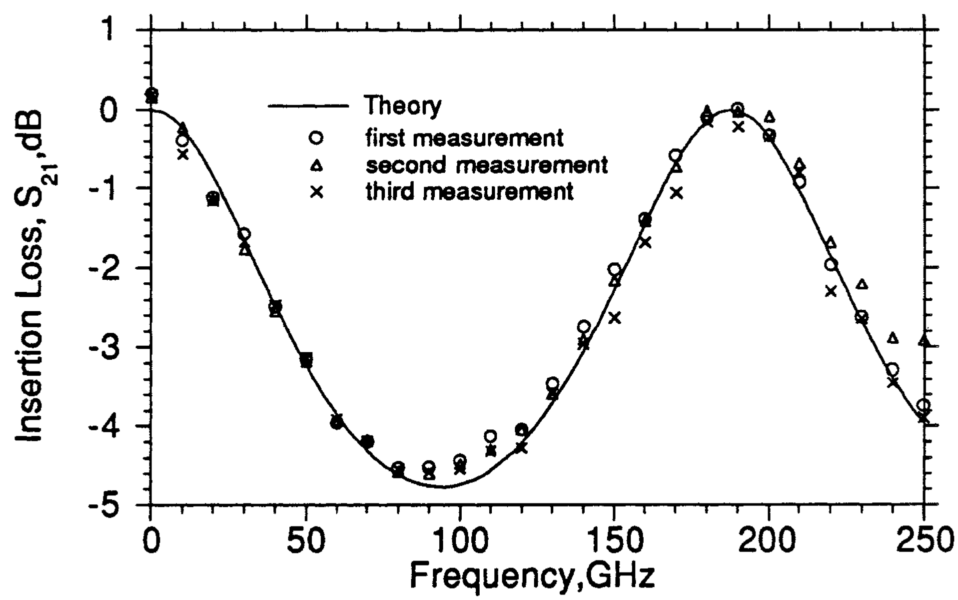

Figure 3: mm-wave measurement of 254 μm-thick alumina test sample.

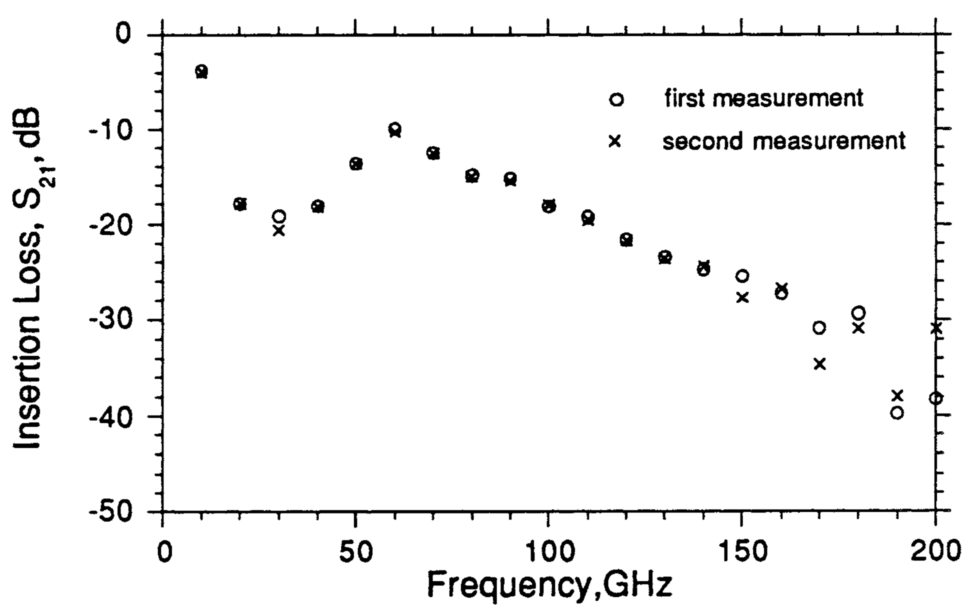

Figure 4: mm-wave measurement of microwave absorber.

We also measured the insertion loss of a microwave absorbing material (Emerson & Cuming FGM-40, 1.0 mm thickness). (Fig.4) A loss minimum is seen at 60 GHz, with the attenuation improving at higher frequencies.

Above 150 GHz, this measurement is limited by the ≈ 35 dB system dynamic range. This dynamic range can be greatly improved by using narrowband signal detection (e.g., a lock-in amplifier).

Conclusion

We have demonstrated a simple and inexpensive system for broadband mm-wave electromagnetic measurements. Reproducible, accurate measurements are possible from 30 to 250 GHz. The combination of the bow-tie antennas and the substrate lenses provides acceptable coupling efficiency over a broad bandwidth, despite the high systems loss (≈ -20 dB between antennas) and the additional (≈ 10 dB) attenuation required to suppress standing waves. The bow-tie antenna is readily integrated with monolithic circuits.

The current system will allow convenient and accurate measurement of materials and emerging mm-wave quasi-optical amplifier arrays. With attainable improvements in the diode cut-off frequency, system bandwidth can potentially be extended to 1 THz.

Acknowledgment

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