Frequency Scalable, Power Control and Active Tuning for Sub-THz Large-Signal Measurements

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Characterizing electronic devices and MMICs at sub-THz frequencies presents several challenges for the instrumentation. While S-parameter measurements can be performed using vector network analyzers (VNA) with mmWave extenders, large-signal measurements require dedicated measurement setups. A novel approach, described here, expands the capabilities of conventional VNA sub-THz S-parameter setups to achieve refined power control, power sweeps and active load-pull.

The increasing performance of semiconductor technologies in terms of f_t and f_{max} is fostering the development of new commercial applications in the mmWave frequency range. Examples can be found in the development of 5G communication with frequencies up to 80 GHz; automotive radar at 77, 94 and 140 GHz; SATCOM; imaging and home entertainment.

Development for commercial applications inevitably includes characterization of single active devices (i.e., transistors) as well as the testing of ICs such as power amplifiers, detectors and radiometers. The first is to extract and verify of the device compact model for frequencies as high as f_t or f_{max}. The latter is to verify IC compliance with the requirements of the final application. Regardless of the scope, the availability of accurate and reliable test instrumentation is fundamental for development.

Active device small- and large-signal characteristics must be determined. The first step is typically the measurement of the S-parameters, which can be achieved using VNAs. Broadband VNAs with coaxial extenders are commercially available up to 220 GHz, while waveguide-banded solutions are available up to 1.5 THz. Limitations of these setups are primarily related to available power, losses in interconnections with increasing frequency (especially for broadband coaxial setups) and the difficulty of controlling power delivered to the device under test (DUT) when waveguide-banded extender modules are used.

For large-signal measurements, one of the most popular techniques is load-pull. Passive tuners are available commercially for frequencies as high as 110 GHz,[1] but performance is generally limited by increased losses at mmWave frequencies, which limits the reflection coefficient that can be presented to the DUT load. Commercial active load-pull systems are currently only available for frequencies lower than 40 GHz.[2] Few examples of active load-pull systems exist in the literature at higher frequencies,[3-4] and they are all based on dedicated implementations that are generally not scalable.

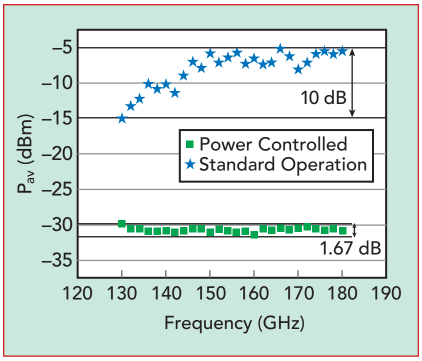


Fig. 1 Output power of a commercial WR5 waveguide extender module showing the nominal output power and a constant –30 dBm set with MMW-STUDIO.

This article describes a measurement approach employing a conventional mmWave VNA with waveguide-banded extenders that has refined power control and power sweep capabilities at any frequency bandwidth covered by the waveguide extenders. With small modifications, the setup can be enhanced to include active tuning capabilities, becoming the first scalable active load-pull setup for sub-THz frequencies.

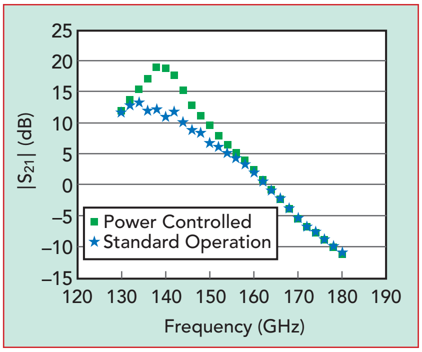


Fig. 2 Measured gain vs. frequency of a two-stage, 130 nm SiGe BCMOS amplifier using waveguide extenders, comparing nominal power from the extender to power control.

POWER CONTROL LIMITATIONS

For conventional VNA measurements, dynamic range is maximized through power control, which is achieved with the hardware using a feedback architecture called automatic level control (ALC). When mmWave waveguide extenders are used, ALC is implicitly excluded from the measurement loop. Due to the absence of an ALC within the extenders and the nonlinear nature of the internal components, the power available from the source can vary significantly within the waveguide band. An example is shown in ***Figure 1***, where the output power (P_{av}) of a commercially available WR-05 VNA extender is displayed, with a nominal fixed power at the RF input port of the module. In the figure, the power fluctuation is on the order of 10 dB. Similar values can be expected at all bandwidths, depending on the manufacturer.

This lack of power control to the DUT has different implications on the measurement accuracy of active devices. When performing small-signal measurements, if the power level at the input of the DUT fluctuates and cannot be properly controlled, the risk is to either drive the device into an incorrect operating regime—compromising the small-signal characterization—or to reduce the input power level to ensure proper operation and restrict the dynamic range of the measurement.

An example related to reduced power control capability is illustrated by De Martino et al.[5] in the characterization of a 140 GHz power amplifier. When the DUT, a two-stage 130 nm SiGe BiCMOS amplifier, is characterized using waveguide extenders with a nominal output power, the S-parameters are incorrectly represented in the frequency range between 135 and 160 GHz (see ***Figure 2***).

COMPUTER-AIDED POWER CONTROL AND SWEEPS

The absence of ALC when using mmWave waveguide extenders can be circumvented using a dedicated software control loop. Consider the simplified schematic of a conventional VNA setup for mmWave measurements employing extenders, shown in ***Figure 3a***, with the addition of an external computer and a power sensor for power calibration. As described by Galatro et al.,[6] power control can be achieved with the following steps (see ***Figure 3b***):

1. S-parameter calibration at the waveguide reference planes.
2. Power calibration by connecting a power sensor to waveguide port 1 and measuring the absolute power during a frequency sweep.
3. Power leveling: nonlinear power responses of the extender modules are characterized over large

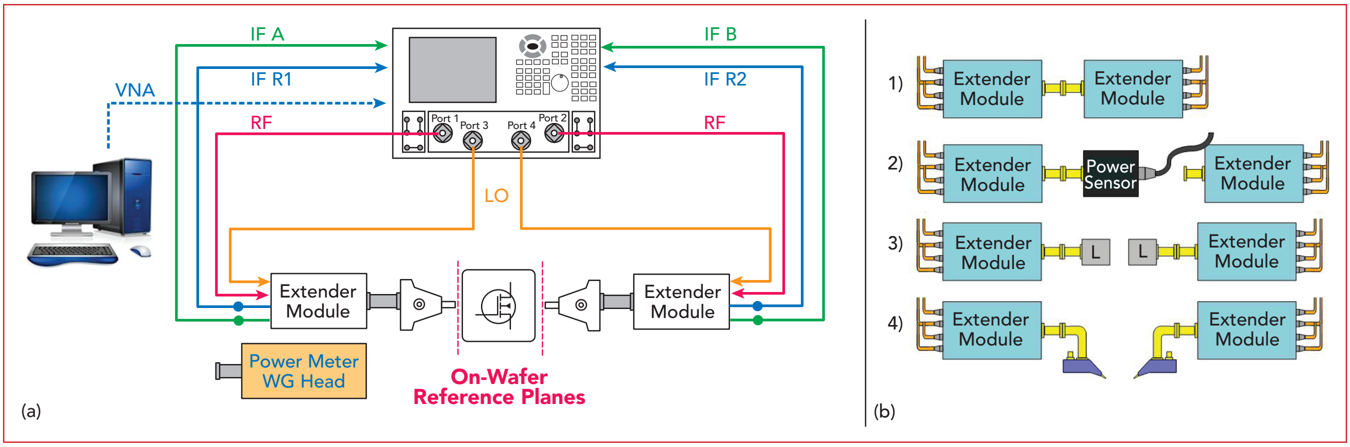


Fig. 3 **Conventional mmWave measurement using waveguide extenders with a 4-port, two-source VNA (a) and the four-step calibration procedure (b).**

sweeps of input power and frequency while measuring the power delivered at the waveguide test port directly using the VNA receivers. This uses the power calibration performed in Step 2.

4. On-wafer calibration shifts all the calibration reference planes (S-parameter, power and leveling) to the desired on-wafer reference plane.

After this four-step procedure, it is possible to accurately control and measure the power provided to the DUT using the high dynamic range and speed of commercial VNAs, as the use of slow and low dynamic range power meters is limited to the power calibration in Step 2.

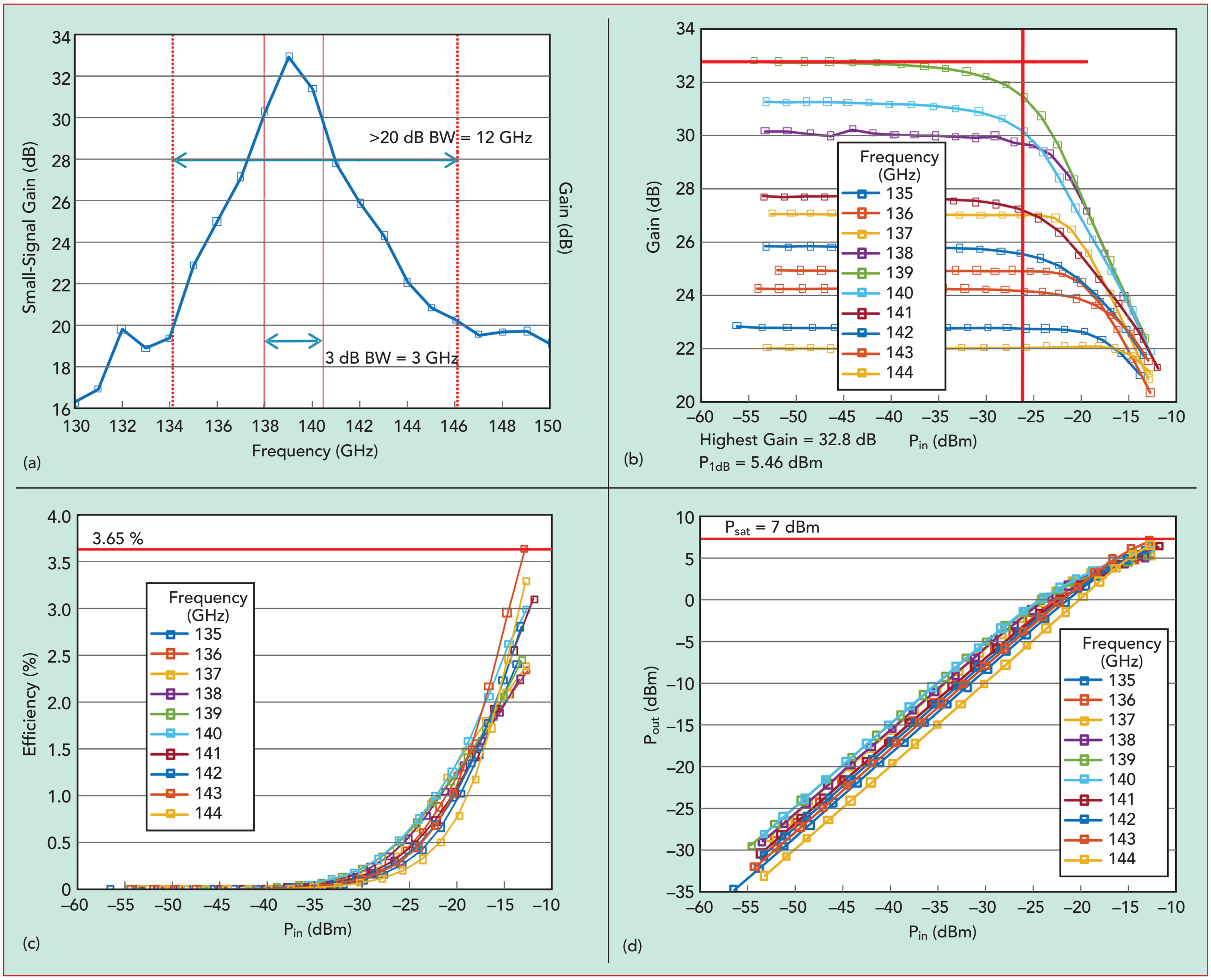
IMPACT OF POWER CONTROL

The capability of controlling power during S-parameter measurements alleviates measurement inaccuracies related to improper device driving. For example, the device described by De Martino was tested using the power control procedure described above and embedded in MMW-STUDIO, a software platform developed by Vertigo Technologies and TU Delft for accurate sub-THz measurements. In this case, the power is maintained at −30 dBm over the entire frequency range (see Figure 1) to ensure small-signal operation. This ensures correct measurement of the S-parameters as shown in Figure 2, where S_{21} is accurately characterized over the entire bandwidth.

The four-step procedure described enables doing more than just controlling power during S-parameter measurements. The capability of controlling and measuring power can also be used to perform power sweeps to derive large-signal characteristics such as gain compression. ***Figure 4*** shows measurement results for power sweeps at different frequencies of the PA described above. Note that the measurement of approximately 250 data points took only about 4.5 minutes, compared to 2 hours to properly perform all the measurements using a power meter setup.

SUB-THz ACTIVE LOAD-PULL

As shown in the previous section, using a four-step calibration and the aid of external computation enables large-signal measurements at mmWave frequencies by employing off-the-shelf equipment designed for small-signal measurements, i.e., the same equipment commonly used for



▲ Fig. 4 Measured performance of a two-stage, 130 nm SiGe BiCMOS amplifier, showing the small-signal gain vs. frequency (a), gain vs. P_{in} (b), efficiency vs. P_{in} (c) and P_{out} vs. P_{in} (d).

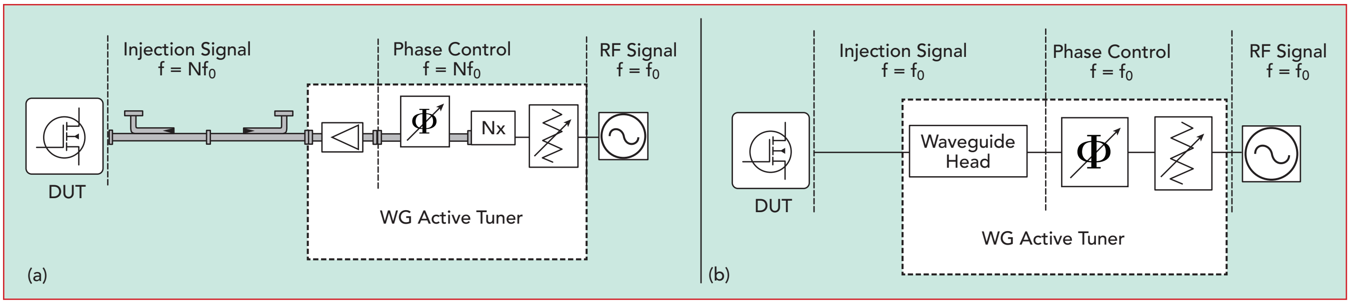


Fig. 5 **Two active tuner implementations: modulating the injected signal after (a) and before frequency multiplication (b).**

simple, non-power controlled, S-parameter measurements. The large-signal capabilities of the setup, however, are limited, and only matched measurements can be performed, since the load or source impedance presented to the DUT cannot be changed with respect to the system intrinsic reference impedance.

To perform more advanced measurements (i.e., active load-pull), the hardware setup needs improvement. The realization of an active load-pull setup requires an active tuner, which changes the impedance condition by properly injecting a defined signal, controllable both in phase and amplitude, into the DUT terminal. Considering the system previously described, while it is possible to modulate the power injected into the DUT, no phase control is available.

To incorporate phase control, a programmable phase shifter must be inserted into the signal injection path. The intuitive solution is to place the phase shifter just before the reflectometer, enabling phase modulation directly on the frequency-multiplied signal (see ***Figure 5a***). This implies modification of the mmWave extender by employing a mmWave phase modulator. While suitable from a measurement perspective, the high cost of such a component with the complexity of a hardware modification inside a mmWave extender makes this solution unrealistic. If, however, the phase shifter is placed before the mmWave extender (see ***Figure 5b***), phase modulation is performed on the RF signal before frequency multiplication, thus at a lower frequency with respect to the measurement. This allows more flexibility and a lower cost, since lower frequency components are used for the phase shifter and the waveguide extender need not be modified.

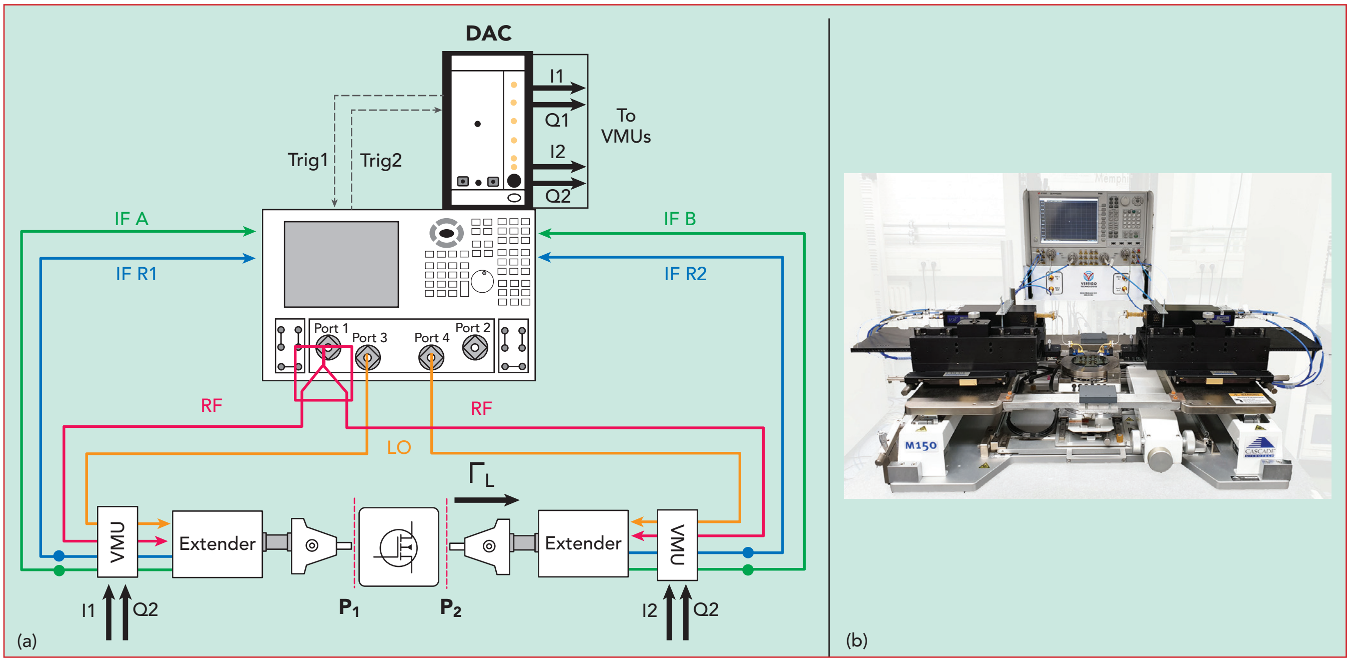


Fig. 6 **The scalable active load-pull test bench for measurements at sub-THz frequencies (a) and view of the complete on-wafer active load-pull system (b).**

FREQUENCY SCALABLE ACTIVE TUNER

Once the topology of Figure 5b is chosen, the actual implementation must be defined. The choice of the waveguide head is defined by the specific frequency range, which, in principle, is arbitrary, as it does not affect the lower frequency hardware. For the amplitude and phase modulation, appropriate components must be chosen. In the case of MMW-STUDIO, amplitude (power) modulation of the injection signal is obtained directly from the RF source of the VNA, while power control is achieved by means of calibration.

For an open loop active load-pull architecture, one of the main requirements is phase coherence between the injected waves at the input and the output of the DUT: the two injected signals must share the same time base. The easiest and most reliable approach is for the two injected waves at the test ports to share the same RF source.[7] If that is the case, and it is desired to use just one RF source of the VNA to control both injections, it is not possible to independently control the power at each port with the same source. If independent power modulation at the two ports is required, another solution must be used. The use of I/Q modulators, as in mixed signal active load-pull[8] at mmWave frequencies,[6] could allow both power and phase modulation for each port, independently. The main difference with mixed signal active load-pull is that signal modulation is performed at a different frequency than the measurement frequency.

Using these considerations, the classical schematic of Figure 3a is modified in ***Figure 6a*** to achieve active load-pull capabilities. Figure

6a is a simplified block diagram of the implementation realized by Vertigo Technologies, where the I/Q modulators are embedded in general vector modulation units (VMU). The VMUs are both driven by port 1 of the VNA through a power splitter, to ensure total phase coherence, at a fixed power. The I/Q modulators are used as phase/amplitude modulators with DC signals (I and Q) generated through a high bit count (24-bit) digital-to-analog converter that is synchronized with the VNA through a handshaking loop to ensure high speed. The frequency at which the VMUs operate is the same as the RF input frequency of the extender modules, typically in the range between 5 and 20 GHz for most commercially available extenders for output frequencies to 1.1 THz. The signal modulated by the VMU is presented to the extenders and is up-converted to the desired frequency. The up-converted signal becomes the injection signal for the active tuner; using an iterative procedure, it is possible to perform active load-pull measurements.

TABLE 1

LOAD CONTROL STABILITY VS. FREQUENCY

Frequency (GHz)	Stability of $\lvert\Gamma L\rvert$ (Standard Deviation)	Stability of $\angle\Gamma L$ (Standard Deviation – Phase)
96	0.002	0.05
140	0.0035	0.33
180	0.0016	0.17
288	0.001	0.29
500	0.0046	0.57

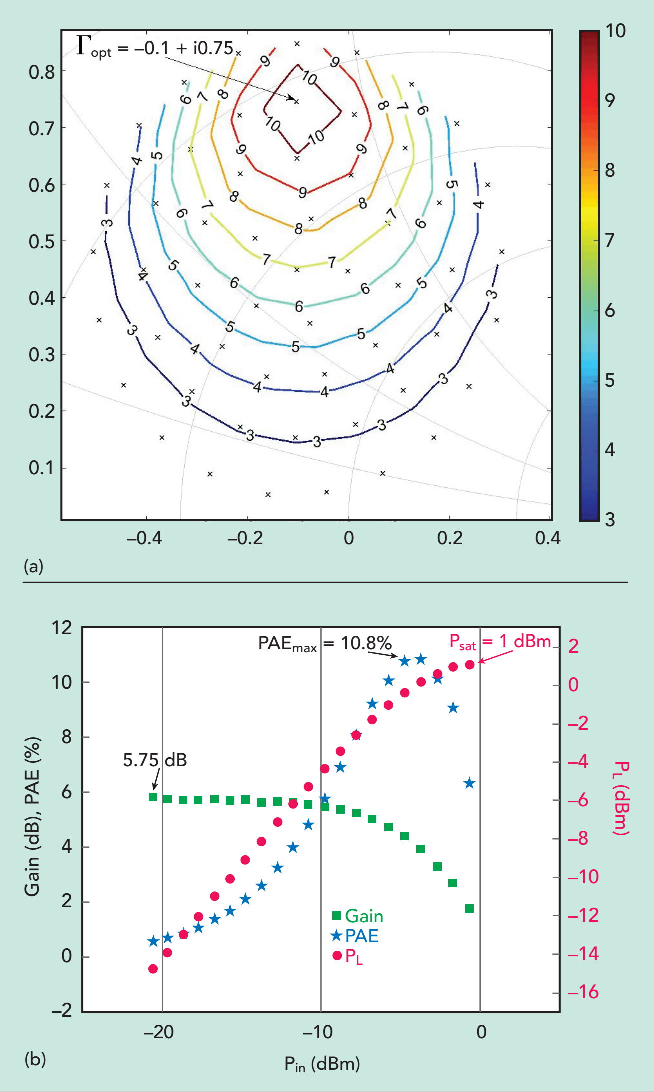


Fig. 7 Active load-pull measurements of a two-fingered, 130 nm SiGe BiCMOS HBT at 125 GHz, showing the PAE contours (a) and the gain, PAE and power delivered to the load at the optimum PAE load (b).

Figure 6b shows a practical implementation of a complete on-wafer active load-pull system working in the WR6.5 waveguide band (110 to 170 GHz). The VMUs for both the input and the output are conveniently assembled in a single rack-mount case for ease of mounting and signal distribution. The system of Figure

6b, together with the MMW-STUDIO LP software, can perform active load-pull measurements at any desired load impedance (depending on the DUT and the extender specifications), ideally at every frequency covered by mmWave extenders. This setup has been tested up to 500 GHz with stability better than 0.01 in magnitude and 0.6 degrees in phase. ***Table 1*** shows a summary of load control stability at different measured frequencies.

Figure 7 shows the large-signal characterization of a commercial, double-finger 130 nm SiGe BiCMOS HBT. The test was performed at 125 GHz with more than 54 different loading conditions and an input power sweep from −21 to −1 dBm. ZC140 extender modules from Rohde & Schwarz were used, featuring a nominal available power of 8 dBm. Figure 7a shows the power-added efficiency (PAE) contours, identifying the optimum loading condition for peak PAE: $\Gamma_{opt} = -0.1 + i0.75$. Figure 7b shows the measured gain, PAE and power delivered to the load (P_L) versus the input power, P_{in}, at Γ_{opt}. To the authors' knowledge, the results of Figure 7 represent the first published active load-pull measurements of an active device at frequencies higher than 110 GHz.

CONCLUSION

With the aid of software, dedicated calibration and small hardware modifications, it is possible to expand the capabilities of conventional waveguide extender-based VNA setups to perform accurate power control, power sweeps and active load-pull measurements in the sub-THz frequency range. The described approach is scalable to every frequency band covered by mmWave waveguide extenders and has been tested to 500 GHz. Measurements of commercial BiCMOS devices at 125 GHz show the capability of this approach to fully characterize realistic devices using off-the-shelf equipment.■

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