Custom chipset and compact module design for a 75–110 GHz laboratory signal source

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Abstract

We report on the development and characterization of a compact, full-waveguide bandwidth (WR-10) signal source for general-purpose testing of mm-wave components. The monolithic microwave integrated circuit (MMIC) based multichip module is designed for compactness and ease-of-use, especially in size-constrained test sets such as a wafer probe station. It takes as input a cm-wave continuous-wave (CW) reference and provides a factor of three frequency multiplication as well as amplification, output power adjustment, and in situ output power monitoring. It utilizes a number of custom MMIC chips such as a Schottky-diode limiter and a broadband mm-wave detector, both designed explicitly for this module, as well as custom millimeter-wave multipliers and amplifiers reported in previous papers.

Keywords: millimeter-waves, signal generator, active multiplier

(Some figures may appear in colour only in the online journal)

1. Introduction

Commercially-available signal sources (or frequency extenders) for millimeter wave frequencies are often bulky, expensive, and do not provide for direct leveling and/or readout of the signal power. One must usually combine them with external waveguide couplers, power meters, and controllable attenuators in order to set and maintain a desired power level, even approximately. The end result is a mass of waveguide plumbing that is time-consuming to set up and difficult to integrate with test sets designed for small devices-under-test (DUTs)—such as a wafer probe station.

In this paper we report on the development of a compact WR-10 signal source, comprising an active multiplier chain with an integrated manual attenuator and digital readout displaying the high-frequency output power in real time. The module is optimized for both compactness and ease-of-use in a component-level development environment. As such, it works as a standalone unit, requiring only DC power and a CW reference signal which can be provided at low power by coaxial cable from a standard laboratory synthesizer. No external computer control or software is needed, nor does the low-frequency reference source need to be located close to the device under test.

This work builds upon a previous attempt at such a laboratory signal source [1]. However, that work was completed nearly 15 years ago, and much improvement has been made since then in embedded micro-electronics and millimeter wave amplifier technology. This makes the current re-optimization a timely effort for the next generation of millimeter wave programs.

An overview of the signal path and the module construction is given in section 2. The individual custom MMICs and other components will be described in sections 3 and 4. Finally, test data for the complete module will be presented in section 5.

2. Module overview

A block diagram of the signal source module is shown in figure 1 and the physical layout of the interior is shown in figure 2. The input is provided by a 2.92 mm coaxial connector interface which supports frequencies up to 40 GHz. It
is coupled to the MMIC chain through a perpendicular coax to microstrip transition [2].

The first active component is a Schottky-diode MMIC limiter which, along with a fixed attenuator pad, protects the following amplifier stage from being over-driven. The amplifier—commercially available HMC-ALH140 from Hittite Microwave (now Analog devices)—was selected for its moderate output power and flat gain in the band of interest (25–37 GHz), however the desired operating point of about 1 mW input is very close to the absolute maximum input power rating of 4 mW [3]. The limiter was therefore deemed a necessary component to prevent damage to the amplifier during casual laboratory use.

Following the amplifier is a broadband tripler using an anti-parallel diode pair to suppress even harmonics. Reported previously [4, 5], the tripler is capable of producing up to 1 mW of power in the 75–110 GHz frequency range when fully driven with >50 mW. In the system reported here, the drive power is somewhat less, about 10 mW, resulting in higher conversion loss but also greater durability.

The tripler output is then amplified with a pair of short gate-length pHEMT GaAs power amplifiers [6]. With a flat gain of 12 dB each, these deliver a maximum output power of around 20 mW across the waveguide bandwidth. This is sufficient to serve as either an RF test tone or a local oscillator to pump a millimeter wave mixer in most laboratory experiments.

Although the module operates without internal filtering, a degree of spectral purity is provided by the tripler anti-parallel design. Measurements at these power levels [4] show that the 4th harmonic is suppressed by at least 20 dB, and the 2nd harmonic by almost 50 dB. The 5th harmonic is stronger, only about 10 dB below the desired tone, but at greater than 125 GHz is far enough out of band that the gain of the subsequent power amplifiers has dropped significantly.

Next, a variable attenuator is used to adjust the output power of the signal source as needed for specific test requirements. The attenuator is made using a 100 Ω tapered resistive vane that slides into the waveguide through a longitudinal slot in the broad wall (where the lateral current crossing is zero). The position of the vane is controlled by a manual micrometer.

Following the attenuator is a waveguide coupler based on a multi-aperture Bethe-hole design [7]. The coupled signal is directed to a MMIC square-law detector. The detected voltage passes through the split block with a coaxial feedthrough to a circuit board where it is monitored by an Atmel ATmega328P microcontroller (see figure 3). An internal lookup table is used to convert this voltage to power units in dBm, which is then written out to an array of 7-segment LED displays, viewable through a clear optical-grade epoxy window in the lid of the housing.

3. Custom chips

A number of custom MMIC chips were required to complete this module. Two of them—the tripler (listed in figure 1 as 93TRP1) and post-amplifier (MMPA107B)—were reported in previous publications [4–6]. The others, a microwave limiter and a millimeter wave square-law detector, were designed explicitly for this module and were fabricated on a multi-project wafer in the BES Schottky diode MMIC process by united monolithic semiconductors (UMS). The design and test results for these two chips are reported below.

3.1. Microwave limiter

As described in section 2, the microwave pre-amplifier in this module is intended to operate relatively close to its absolute maximum power rating, necessitating a limiter in front of it for protection. A photograph of the chip is shown in figure 4(a). The design of this limiter is straightforward, comprising a microstrip though-line with anti-parallel diode pairs connected in shunt. Two versions were designed, having either a single pair or two pairs of anti-parallel diodes spaced a quarter-wavelength apart. Both sets were printed on the same chip, allowing the module designer to select between two
different levels of limiting simply by rotating the substrate 180°. For this module, the two diode-pair channel is used. In both cases, a microstrip taper is used to better match the impedance of the parallel diodes to 50 Ω.

For simplicity, the limiter is designed for passive operation only—that is, no bias is provided to the diodes. This avoids complex bias tees and makes it easy to ensure broadband operation up to 40 GHz, however the saturation level depends solely on the diode parameters and cannot easily be controlled. Intrinsically, it limits at too high a power level for the pre-amp it is meant to protect. Therefore, the limiter is used in combination with a following attenuator pad to keep the output power delivered to the pre-amp within specs.

Measured versus simulated performance at 25 GHz input is plotted in figure 4(b) (curves at other frequencies in the operating band are similar). The linear part of the curve, below about 5 dBm input, shows that the limiter incurs approximately 0.6 dB of loss at 25 GHz. At the high end of the operating band this loss increases to 1 dB. The measurement was carried out to the maximum extent of the available test equipment (in this case about +12 dBm after accounting for the loss of the wafer probes). This was sufficient to observe the saturation of the limiter.

The saturation point is about 2 dB lower than was predicted—ironically, an improvement in this case, since higher saturation would have required a larger attenuator and resulted in less overall module gain. The error is likely due to the diode model, which was intended for mixer applications and may be inaccurate for this kind of usage. For example, the foundry’s documentation on the diode model used states that it accurately describes both the forward and reverse bias conditions, but does not account for avalanche breakdown. The excess current in this region would tend to short out the through-line of the limiter, increasing effective saturation. The avalanche region is not considered a durable long-term operating condition for mixer applications, but is acceptable in a limiter where the condition should be encountered only infrequently as a stop-gap protection measure.

The measured performance of the detector chip forms part of the WR-10 source module calibration and will be discussed in section 5.
4. Waveguide components

Following the final millimeter wave power amplifiers, the output signal is coupled to WR-10 waveguide using an E-field longitudinal probe. The remainder of the primary signal path is in waveguide, and comprises two additional components for output power monitoring and control.

4.1. Variable attenuator

The first such component is a variable attenuator. It consists of a retractable absorbing vane that enters the waveguide through a slot in the broad wall. The motion of a vane is controlled by a manual micrometer, oriented such that the axis of motion is oblique to the longitudinal axis of the guide, thereby using the full range of motion of the micrometer (about 6.35 mm) to position the vane within the 1.27 mm projected height of the waveguide.

While solid-state, voltage-variable attenuators in MMIC form are readily available (or could be designed, if needed), they typically require two control voltages that are non-linearly dependent upon one another, necessitating some kind of micro-processor control. This in itself is not difficult to implement with an external computer, and may have even proven more convenient in a production environment where computer-control can be used for scripting a pre-determined array of measurements, however in research testing the setup time associated with automation is often an impediment to rapid adaptation or real-time trouble-shooting. For this reason, a manually-controlled variable attenuator that needs no external computer was deemed more desirable in the intended application scenario for this development.

The curvature and sheet resistance of the absorbing vane were selected based on a 3D electromagnetic simulation, given the constraints of the available resistive materials (especially substrate composition and thickness). The simulation model and predicted performance are shown in figure 7. The frequency response becomes somewhat unpredictable at the very deepest levels of attenuation, but is flat for attenuations up to 20 dB.

4.2. Bethe-hole coupler

A multi-aperture Bethe-hole coupler was designed for this module [7]. The physical dimensions are shown in figure 8(a). First, a wall thickness of 0.127 mm was selected for manufacturability and achievable coupling for a modest number of apertures. Next, the offset of the apertures from the center-line of the waveguide was optimized to achieve the flattest coupling response per aperture pair across the frequency...
band. Several pairs of coupling apertures were then arranged 1.016 mm apart, approximately quarter-wavelength spacing, to achieve the desired coupling. Finally, the diameter of the outermost coupling apertures was adjusted to optimize the impedance match. The final simulation model is shown in figure 8(b).

The predicted performance of the coupler is shown in figure 9. It achieves a flat coupling response of about 15 dB, with better than 30 dB directivity over most of the band. Return loss and insertion loss are also near perfect for this component. While the coupler was not manufactured as a standalone part for independent verification, prior experience with such couplers has given the authors a very high degree of confidence in the accuracy of their simulated performance. The actual response of the coupler will be accounted for, in combination with other elements, during the overall calibration of the module.

To fabricate this part, all twelve coupling apertures were drilled from the outside of the split block through the broad wall of the waveguide. As a consequence, the same holes that collectively provide 15 dB coupling between waveguides internally are present in the external wall of the housing. However, the outside wall of the block is an order of magnitude thicker than the thin internal wall separating the waveguides. Since the apertures are well below cutoff for the frequency band of interest, the coupling through them is exponentially dependent on this thickness. As a result, the leakage through these residual holes in the outer wall which remain as an artifact of the machining process is quite negligible.

5. Module test data

Two identical modules were built, calibrated and tested. The pair is needed for future experiments with down-converters where both an LO and an RF test signal are required.

Calibration was performed by first programming the ATmega328P microcontroller to display simple ADC counts. The output power as a function of frequency and attenuator micrometer setting was then measured with a power meter and recorded. A logarithmic curve was then fitted to the data and the resulting lookup table programmed into the microcontroller so that the display reads in dBm. This calibration simultaneously accounts for the insertion loss of the vane attenuator, the coupling of the Bethe-hole coupler, and the responsivity of the detector. These integrated elements were not validated individually, as that would have required multiple independent test structures and, since they would be calibrated as an ensemble anyway, the accuracy of electromagnetic simulations was deemed accurate enough for the purposes of this construction.

Calibration curves for both modules are shown in figure 10. The spread in measured points around a particular power
setting result from the combined frequency-dependence of the detector responsivity as well as the coupling curve of the coupler, which were described in sections 3 and 4. The overall accuracy of the power monitor is better illustrated by figure 11, which shows the actual output power measured with a power meter when the integrated readout displays 0 dBm (1 mW). Again, the deviation below 85 GHz and above 110 GHz is a consequence of the coupling curve of the coupler, and of the frequency-dependent responsivity of the detector (the dominant contribution likely coming from the latter). Since the module has no internal frequency counter, its calibration has no means of correcting for these effects—but the user can do so, if he or she desires, given knowledge of the frequency input to the module, using this plot. Both the coupler and the detector were designed to have as flat a frequency response as possible to minimize this effect, and the very small in-band deviation (less than 1 dB) indicates the success of that effort.

A photograph of module A in operation illustrates similar agreement between the integrated readout and a calibrated power meter at higher power levels in figure 12.

The maximum output power of the modules is determined by the saturation level of the power amplifiers and subsequent losses in the waveguide probe, the attenuator (when the vane is fully retracted), and the coupler. Because the latter two are all-waveguide parts, the probe itself is likely to be the dominant contributor to this loss.

Based on the known saturation level of the amplifiers and estimated losses, we should expect about 10 dBm available power across most the band. The measured maximum output power is shown in figure 13 which is in good agreement with this prediction. The roll off below 85 GHz is believed to be due to the power amplifier gain dropping out. Previous measurements in [6] did not extend this low in frequency, but the amplifier’s simulated performance does show a sharp drop in gain below 85 GHz.

6. Thermal and noise considerations

Although temperature was not explicitly modeled in this design, any affects it has on conversion efficiency and/or saturated power are automatically accounted for by the in situ power monitoring. The design of the mm-wave detector in turn accounts for its own temperature dependence via the reference channel which is on the same piece of GaAs and thus should experience the same temperature rise as the primary detection channel. In practice, the authors have found that saturated output power varies only slightly, about 1 dB, after heating up to its final temperature. Heat sinks were subsequently added to the module housing to help minimize this effect and protect the internal electronics from pro-longed operation.
Additionally, while a test set capable of accurately characterizing the excess noise ratio (ENR) of this signal source was not constructed, the design of the signal path leverages the authors’ experience in design of local-oscillator multiplier chains for highly-sensitive mm-wave superconducting mixers. Previous experiments [8] have shown that keeping all active elements in a state of compression at all frequencies is key to suppressing the build-up of AM noise on the carrier, and even attenuating such noise which is introduced by the input signal. Measurements with a Rohde and Schwarz 46 GHz FSU Spectrum Analyzer show, not surprisingly, that the noise power contributed by this signal source in operation is below the noise floor of that instrument.

7. Conclusion

A compact WR-10 signal source was designed as a multichip module, and two prototype units were built and tested. Measurements are in good agreement with predictions for both the individual custom MMIC chips and waveguide components as well as the final assemblies. Both modules deliver up to approximately 10 mW of output power in the 75–110 GHz frequency range. The power is manually adjustable and the modules include an integrated power readout to facilitate rapid prototyping and troubleshooting in laboratory measurements of small devices.

To illustrate the utility of this development, a photograph of the two modules being used simultaneously to probe-test a millimeter wave sideband separating mixer is shown in figure 14. (Note the late addition of the heat sinks which are visible in this photograph.) Crowding around the probes would have made this measurement setup much more difficult using currently available laboratory sources.

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References

[1] Morgan M, Weinreb S, Wadefalk N and Samoska L 2002 A MMIC-based 75–110 GHz signal source IEEE MTT-S Int. Microwave Symp. Digest pp 1859–62
[2] Morgan M and Weinreb S 2002 A millimeter-wave perpendicular coax-to-microstrip transition IEEE MTT-S Int. Microwave Symp. Digest pp 817–20
[3] Analog Devices 2015 HMC-ALH140 datasheet (http://www.analog.com/media/en/technical-documentation/data-sheets/hmc-alh140.pdf)
[4] Morgan M and Weinreb S 2001 A full waveguide band MMIC tripler for 75–110 GHz IEEE MTT-S Int. Microwave Symp. Digest pp 99–102
[5] Morgan M, Bryerton E, Cesarano P, Boyd T, Thacker D, Saini K and Weinreb S 2005 A millimeter-wave diode-MMIC chipset for local oscillator generation in the ALMA telescope IEEE MTT-S Int. Microwave Symp. (doi: 10.1109/MWSYM.2005.1517004)
[6] Morgan M, Bryerton E, Karimy H, Dugas D, Gunter L, Duh K, Yang X, Smith P and Chao P C 2009 Wideband medium power amplifiers using a short gate-length GaAs MMIC process IEEE MTT-S Int. Microwave Symp. (doi: 10.1109/MWSYM.2009.5165753)
[7] Erickson N 2001 High performance dual directional couplers for near-mm wavelengths IEEE Microw. Wirel. Compon. Lett. 11 205–7
[8] Bryerton E, Morgan M, Thacker D and Saini K 2007 Maximizing signal-to-noise ratio in local oscillator chains for sideband-separating single-ended mixers 18th Int. Symp. on Space Terahertz Technology