A Calibrated RF/IF Monolithic Vector Analyzer

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***Abstract* — This work presents the first monolithic integrated circuit that provides precise, scaled measurements of gain and phase difference between two signals up to 3GHz. A 60dB gain range and 180 degree phase range are achieved with 30mV/dB and 10mV/degree scaling, respectively. This function has wide application for in-situ measurement of vector RF parameters and in linearization of transmission systems such as power amplifiers.**

I. INTRODUCTION

The detection and measurement of level and phase difference between two signals is of ubiquitous interest since these quantities describe the transfer function of a generic functional block or system. The knowledge of the gain and phase characteristics of a particular signal chain is essential not only in diagnosing problems but also in dynamically correcting its characteristics. This is particularly relevant in modern communications systems that require some level of autonomous adaptability in a changing environment. Presently, this function is implemented in discrete form most simply with two power detectors, two limiting amplifiers and a phase detector of some type. Such implementations inevitably require calibration of the power detectors and are prone to errors over frequency, power level and temperature. By integrating monolithically a pair of closely-matched power detectors and a high-speed phase detector, a high-precision gain and phase measurement system is possible with no need for calibration. Furthermore, the fully integrated solution consumes significantly less power and board space than a discrete version and offers the possibility of adding convenient features such as scaling and offseting of the transfer functions.

II. LOGARITHMIC AMPLIFIERS

Logarithmic amplifiers (log-amps) compress a signal of large dynamic range into a "decibel-scaled" output. The log-amp transfer function can be described by

$$V_{OUT} = V_Y \, log \, (V_{IN}/V_X) \qquad (1)$$

where V_Y is the *logarithmic slope* expressed in mV/dB, and V_X is the *intercept* specified in volts or dBV. The intercept represents the input level that would yield an output of precisely zero and therefore represents the level to which the measured input is referenced. Using proper design techniques, monolithic log-amps can achieve excellent accuracy in power measurement, particularly if laser trimming is invoked. In practice, the intercept introduces the greatest uncertainty in the measurement accuracy. It can also be shown that the intercept is dependent on the statistical nature of the waveform. [1]

When a pair of nominally identical log-amps are co-integrated and their respective outputs are subtracted as shown in Fig. 1, the intercept term vanishes and the transfer function now becomes,

$$V_{OUT} = V_Y \, log \, (V_A/V_B) \qquad (2)$$

where V_A is one input and V_B is a second input. The final voltage-mode output represents the dB-scaled *gain* defined by V_A/V_B with a slope of 30mV/dB that is traceable to an accurate internal reference. The immediately apparent benefit of this synergistic co-integration is that the dependence on an internal intercept, with its associated sensitivities to temperature, frequency and/or supply voltage, has been eliminated. The measurement process is *fully ratiometric*: the system responds only to the ratio V_A/V_B and is basically insensitive to the actual magnitudes or shapes of V_A and V_B. By laying out the part symmetrically in the package and on the board, high frequency resonances, parasitics and impedance mismatches are also cancelled since they are common to both inputs.

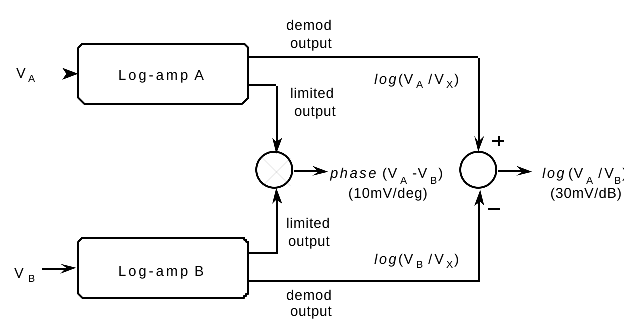

Fig. 1. The Gain-Phase Detector is a versatile monolithic IC based on matched log-amps that generates scaled

measures of relative gain and phase between two high frequency signals.

III. INTEGRATED CIRCUIT BLOCKS

The demodulating log-amps are based on a cascade of limiting amplifier cells whose bandwidth sets the RF capability of the part. The active cross-coupled cascodes with current-feedback emitter-followers shown in Fig. 2 help extend the bandwidth. Briefly stated, the active cascode serves to cancel the effects of transistor C_{JC} in the main gain pair, while the feedback follower reduces the bandwidth compression caused by the input capacitance of the subsequent gain stage. Six stages are used in the gain/phase detector, each having a gain of 10dB. Fig. 3 illustrates that each gain stage in the cascade exhibits a 3dB bandwidth of 5GHz. The entire cascade provides 60dB gain which represents an astonishing gain-bandwidth product of 5THz.

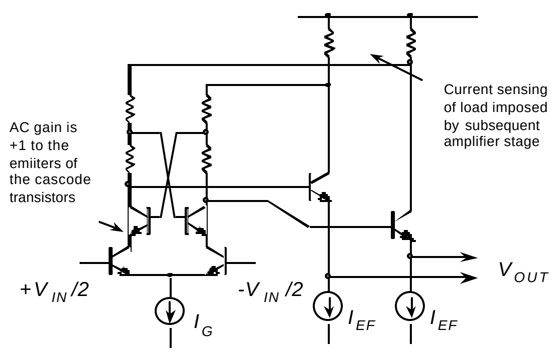

Fig. 2. The log-amp gain cells feature cross-coupled cascodes and emitter followers to extend their bandwidths.

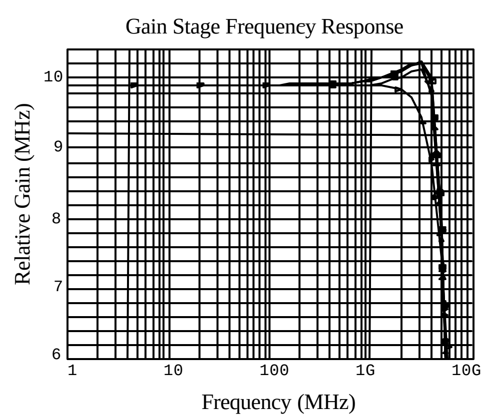

Fig. 3. The gain of each 10dB stage in the.cascade achieves a 3dB bandwidth of 5GHz.

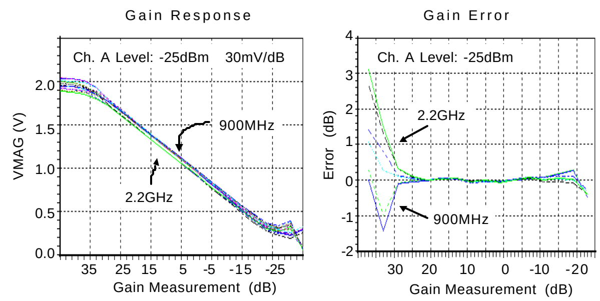

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Fig. 4. The gain measurement response maintains its integrity beyond 2.2GHz with a precise slope of 30mV/dB with <0.2dB error of 40dB range

The demodulation is performed by rectifying cells driven from each gain stage and subsequent low-pass filtering. As shown in Fig. 4, the resulting response to *gain* between channels A and B exhibits the prescribed 30mV/dB (1.8V span for 60dB gain range) with <0.2dB error over a large gain range even beyond 2GHz. Note that the measurement of both gain *and* attenuation is provided centered at mid-scale for 0dB.

The output of the last cell in each channel is usually a hard-limited waveform, approximating a square-wave for most of the useful signal range at the input. When these two limited output signals are applied to a wideband four-quadrant analog multiplier, the average of the resulting product is proportional to the difference in phase angle. As shown in Fig. 5, the multiplier is fully-symmetric with regard to its A- and B-channel response, and the output magnitude is independently controlled by the tail current, I_T. The differential current-mode outputs are converted to single-sided voltage-mode form with a scale factor of 10mV/degree (1.8V span for 180 degrees) again derived from a precise internal reference.

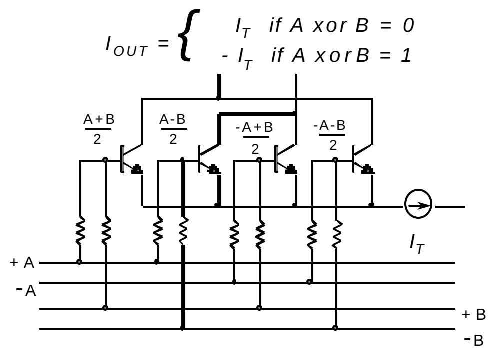


Fig. 5. The one-level phase detector maintains balance beyond 3GHz and does not suffer from different delays along different paths as in the conventional exclusive-OR topology.

With attention to balanced layout and differential signaling, accurate phase measurement is achieved beyond 2GHz. Fig. 6 illustrates the phase detector response to two 1GHz inputs slightly staggered in frequency so that phase can accumulate over time. With a frequency difference of 100MHz, the phase repeats every 10ns. Note that the detection of phase near 0 and 180 degrees at these frequencies degrades as the edges are smeared.

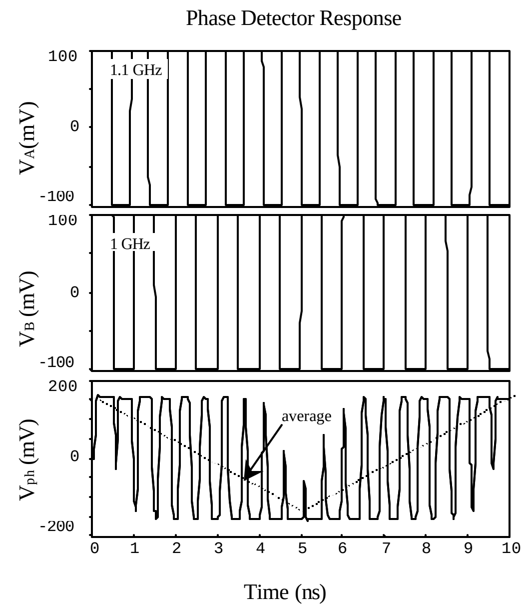


Fig. 6. The phase detector operates well into the GHz range with slight loss of range near the 0 and 180 degree points.

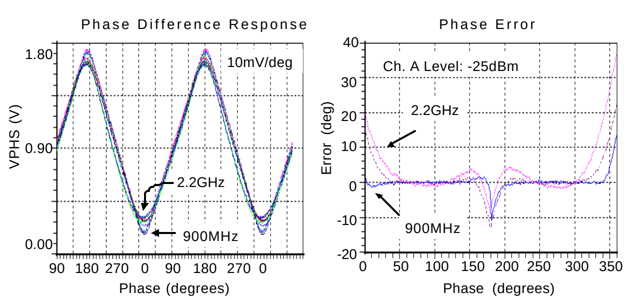
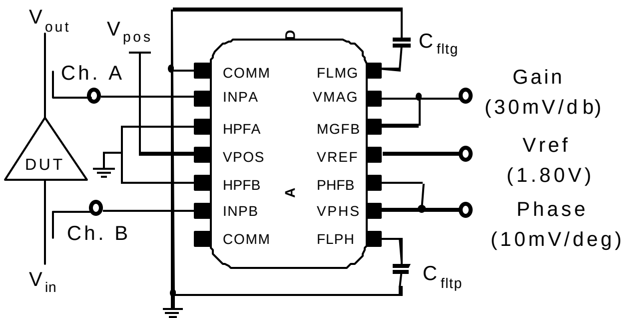


Fig. 7. The phase measurement response shows a precise slope of 10mV/deg with a phase error less than 1 deg over nearly the entire phase range at 900 MHz.

The measured overall phase response is shown in Fig. 7. The prescribed scale factor is preserved at frequencies beyond 2GHz. Phase errors less than 1 degree are achieved over most of the phase range below 1GHz. The rounding of the transfer curves at the 0 and 180 degree phase extremes is symptomatic of the edge ambiguity at higher frequencies.

IV. EXTRA FEATURES

The gain/phase detector is packaged in a 14-pin TSSOP format. It operates from 2.7-5.5V, consuming nominally 19mA, over -40^{o}C to $+85^{o}$C temperature range. Output buffers and set-point inputs allow the internal gain- and phase-scaling to be altered externally and enable operation as a controller. Push-pull output buffers can source or sink 10mA, providing symmetric, fast slew rates when driving



capacitive loads. External capacitors may be used to set the integrating time constants for the gain and phase averaging independently. This enables the part to follow instantaneous phase and amplitude envelope variations or to simply react to the average phase and amplitude. A voltage reference output of precisely 1.80V based on the same standard invoked for the gain and phase slopes is also provided for certain applications in which the outputs must to be offset.

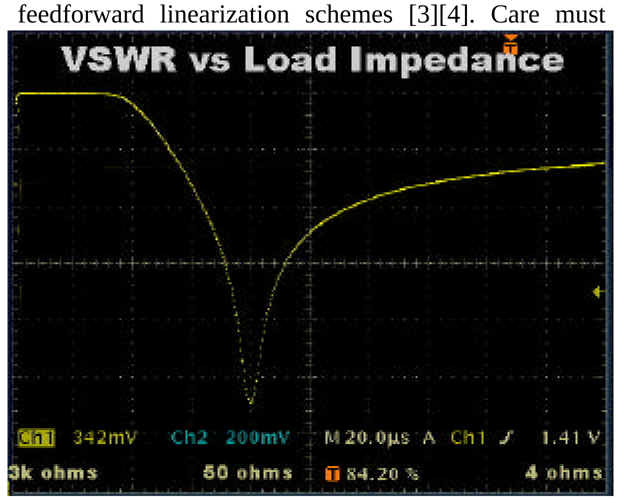
V. Applications

The basic measurement configuration that provides the built-in scaling is illustrated in Fig. 8. The output pins are directly connected to the respective set-point inputs. The DUT can be an amplifier where the gain and phase outputs would correspond to the vector S_{21}. The DUT might also be a mixer where channels A and B would be at different frequencies. In this case the gain output would correspond to the conversion gain. Finally, the DUT might be a set of couplers that sample incident and reflected power to a termination such as an antenna. The gain and phase outputs would represent the vector S_{11}. Fig. 9 shows the measurement of $|S_{11}|$ from a PIN diode as its forward bias is swept. Note that an impedance match is achieved at near mid-bias. The phase and gain scaling can be altered by inserting a resistive voltage divider from the output pins to the set-point pins. The 1.80V reference can be used to re-center the output level by incorporating it into the voltage divider as an offset.

Fig. 8. The basic measurement-mode connection results in the inherent 30mV/dB and 10mV/degree.

Fig. 9. The reflection coefficient of a PIN diode is measured as its forward bias is swept.

The controller configuration given in Fig. 10 essentially consists of gain and phase AGC loops that require the gain and phase measurement system as well as gain and phase control elements. In this configuration, the set-point inputs are disconnected from the gain and phase outputs. The user dials the desired gain and phase as voltages to the set-point pins. The controller gain and phase outputs now drive the gain and phase controlling devices until the DUT achieves the prescribed gain and phase. This integrated function is attractive for feedback and feedforward linearization schemes [3][4]. Care must be



taken to ensure that the loops are dynamically stable and that dynamic ranges are not exceeded within the loops.

VI. Conclusion

A monolithic RF/IF gain and phase measurement system is presented that operates up to 3GHz. A matched pair of jointly integrated logarithmic amplifiers enables accurate level difference between two signals to be measured. A co-integrated single level phase-detector extracts the relative phase information. The gain and phase accuracy remain excellent over supply, process, frequency and temperature due to the matching inherent in the monolithic approach. This function can be used to monitor vector RF parameters and to help in the linearization of transmission systems.

References

[1] AD640 Data Sheet, Analog Devices, Inc., Norwood, MA 02062, pp. 9-10, 1999.

[2] AD8307 Data Sheet, Analog Devices, Inc., Norwood, MA 02062, pp. 7-10, 1997.

[3] S. Cripps, *RF Power Amplifiers for Wireless Communications*, Norwood, MA, Artech House, 1999.

[4] N. Pothecary, *Feedforward Linear Power Amplifiers*, Norwood, MA, Artech House, 1999.

Fig. 10. The controller-mode can be used as a linearizer in either feedback or feedforward systems.