The PicoAmp Distribution Amplifier Module

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• Introduction

The PicoAmp is a 4-channel RF distribution module intended primarily to provide 10 MHz reference inputs to 1-4 PicoPak clock measurement modules.

• PicoAmp Description

The PicoAmp is packaged identically to a PicoPak module, and like that device, it obtains its +5 VDC power from a PC USB port. It has one SMA connector on its rear panel for a +7 dBm nominal RF input from a 10 MHz reference source, and four SMA connectors on its front panel to drive the reference inputs of up to four PicoPak clock measurement modules. Those four RF outputs have the same nominal level as the input. While useful at other frequencies, the outputs have low-pass filters with 12 MHz cutoffs that limit its applicability to 10 MHz or lower. There are LED indicators on the rear panel for DC power and RF input. Photographs of the PicoAmp circuit board and overall package are shown in Figures 1 and 2.

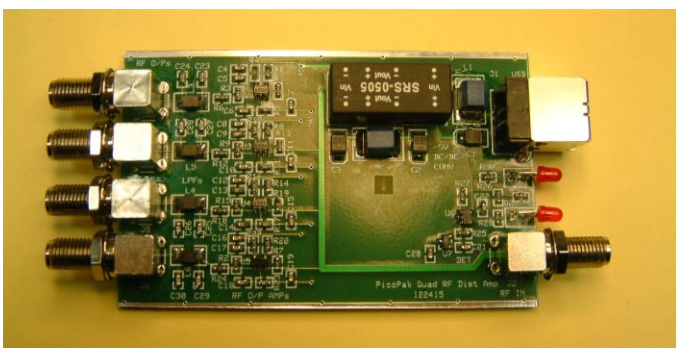


Figure 1. PicoAmp Circuit Board

Figure 2. PicoAmp Package

• PicoAmp Application

The PicoAmp is easy to use with up to four PicoPak clock measurement modules, a reasonable limit to be operated from a single PC. One simply powers it from a PC USB port, drives it from a suitable 10 MHz frequency reference (e.g., a GPS-disciplined rubidium oscillator) and connects it to the reference inputs of the PicoPak modules with suitable SMA cables. To insure measurement integrity, the usual precautions should be taken, including uninterruptable power, mechanical rigidity, and quality, properly-torqued cables. It is desirable, but not necessary, to terminate any unused PicoAmp RF outputs. The PicoAmp contributes a negligible amount of noise to a PicoPak time-domain stability measurement.

Although the PicoAmp provides good channel-to-channel isolation, one should not change its configuration during a measurement run. If doing so is necessary, one must note the reason for any resulting phase disturbance. Similarly, even though they are reasonably immune to temperature changes, one should locate the PicoAmp and its associated PicoPak modules in a thermally-stable environment. The PicoAmp and PicoPak modules do not have ground-isolated RF ports and, under some circumstances, can be subject to AC power-line ground loop interference. RF isolation transformers can sometimes help to avoid that problem, but the simplest way is to operate all parts of the clock measurement setup from a common AC power-line connection or outlet strip. The PicoAmp can be powered from a USB hub or charger.

• PicoAmp Circuit Design

The PicoAmp circuit is shown in the schematic diagrams of Figures 3 and 4.

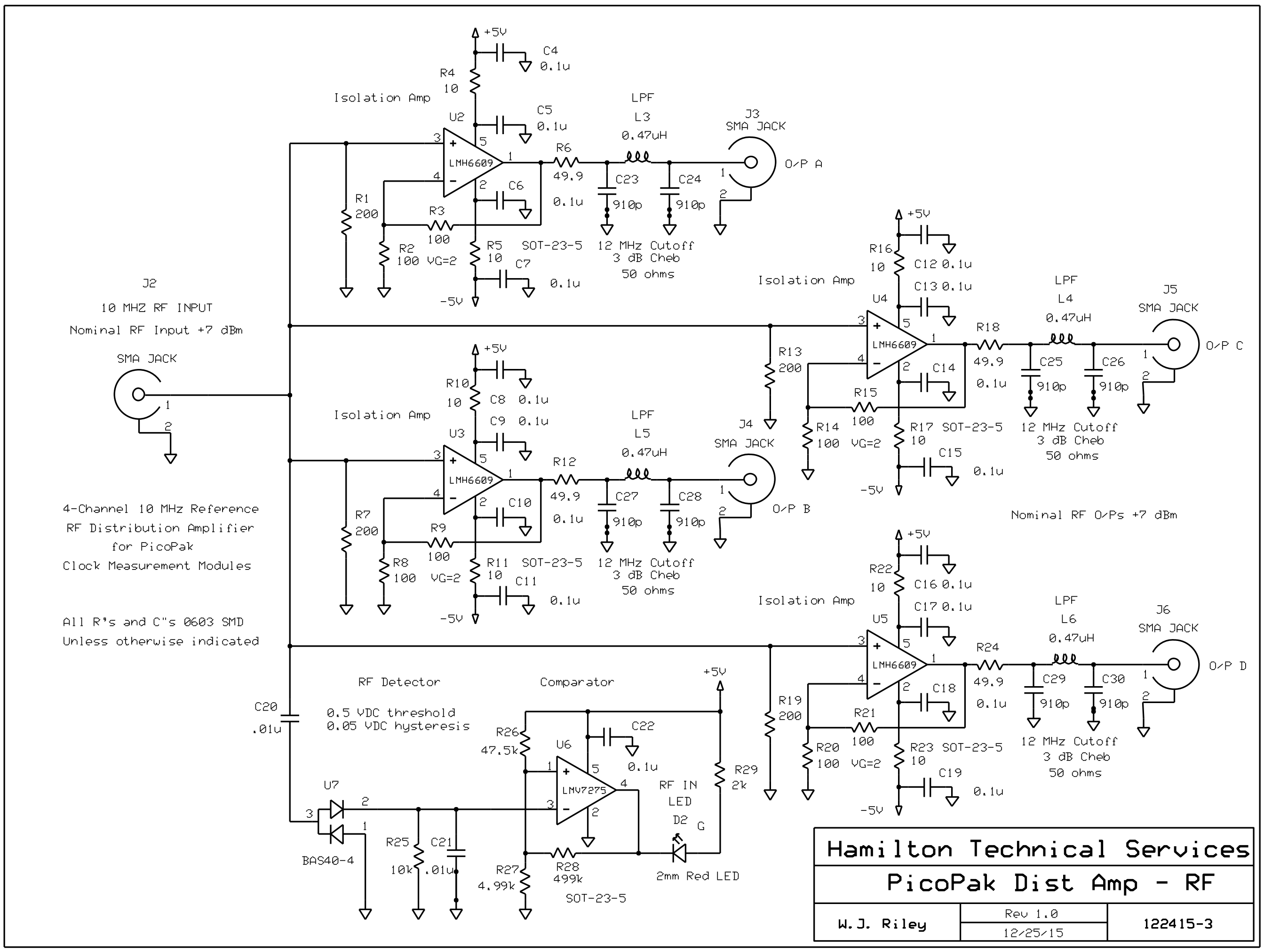


Figure 3. PicoAmp Schematic – RF Section

The PicoAmp RF section comprises RF isolation amplifiers and an RF detector circuit. The amplifiers have 50 Ω input and output impedances and overall unity gain, and are followed by 12 MHz cutoff low pass filters, consistent with their application for 10 MHz reference distribution. They are implemented with LMH6609 wideband op amps powered from ±5V supplies. The presence of RF input is sensed by a full-wave diode detector and a DC level comparator with hysteresis that drives an LED indicator.

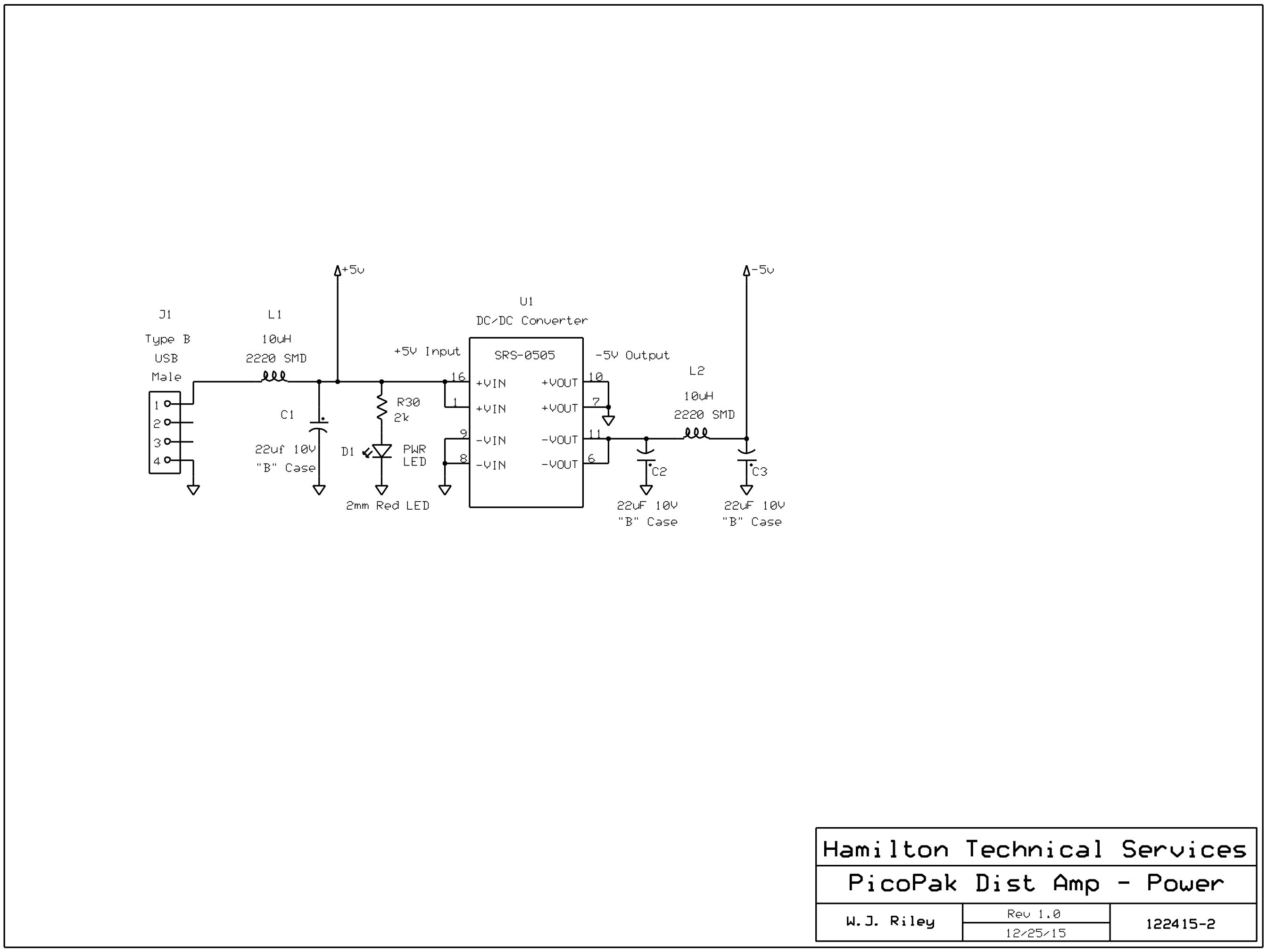


Figure 4. PicoAmp Schematic – Power Section

The PicoAmp power section comprises a USB connector and filter that supplies +5 VDC and a small DC/DC converter module that supplies -5 VDC. The latter is followed by an additional low pass filter to further reduce its output ripple. An LED indicates the presence of DC input power.

The PicoAmp does not communicate with the host PC and has no microprocessor or firmware. It has no hand wiring or adjustable components, and requires no calibration.

• PicoAmp Board Layout

The PicoAmp board layout is shown in Figure 5. It is a 3.10" by 1.95" (80 x 50 mm nominal) double-sided board using mainly surface mount components. Five right-angle SMA connectors provide the RF input and output ports, a Type B USB jack supplies +5 VDC power to the board, and a DIP-style DC/DC converter module provides -5 VDC for the RF amplifiers. The board slides into slots in its extruded aluminum enclosure.

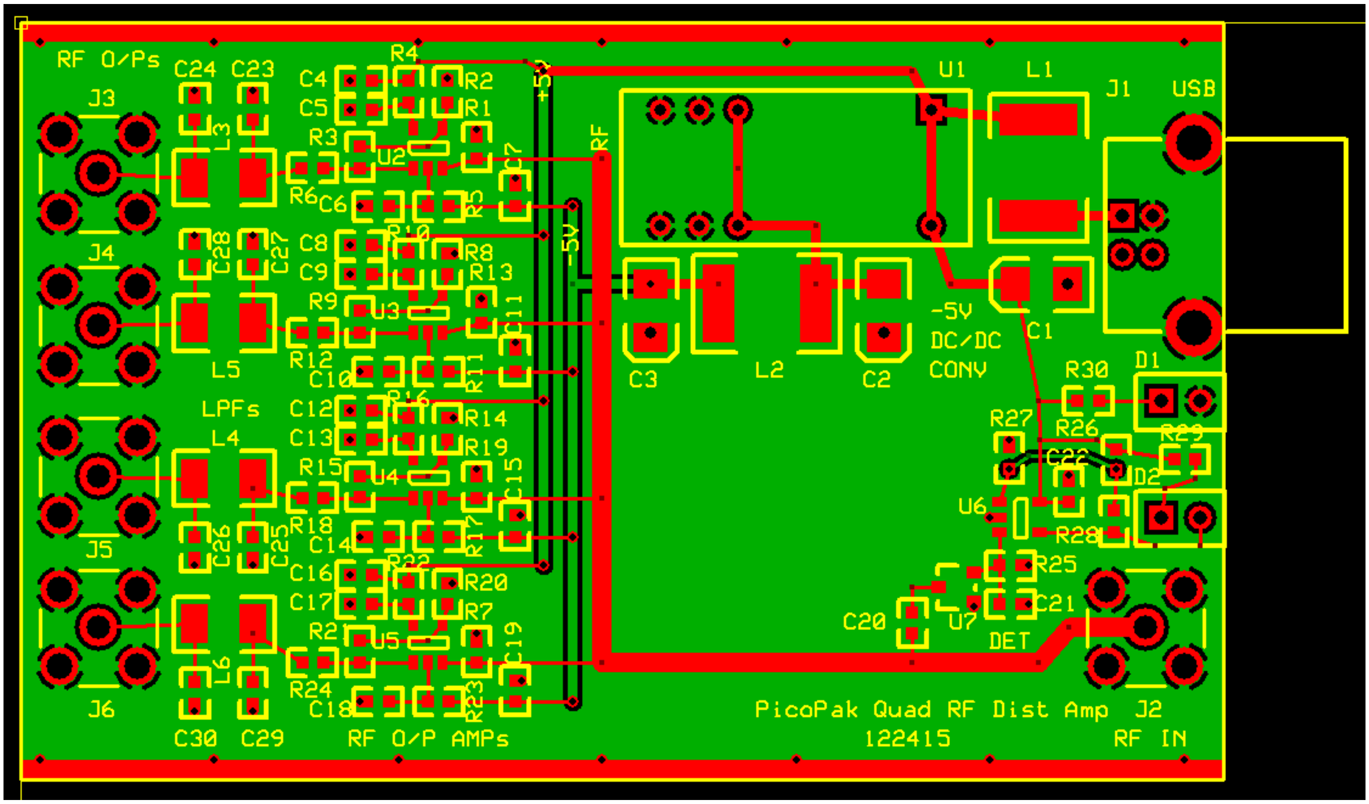


Figure 5. PicoAmp Board Layout

• PicoAmp Package

The PicoAmp package was shown in Figure 2. It uses the same Hammond HM969 3.15" long x 2.13" wide x 0.91" high extruded aluminum box as the PicoPak, with removable end plates, black trim and four bottom feet. The PicoAmp can be opened most easily by removing the nut and washer holding the rear SMA connector and sliding the board out from the front, leaving the four front SMA connectors attached.

• PicoAmp Testing

The following tests were conducted on a prototype PicoAmp to verify its suitability to distribute PicoPak reference signals and to draft its specifications. Unless otherwise noted, these tests were conducted at 10 MHz with a +7 dBm nominal input level and all outputs terminated into either a PicoPak reference port or a 50 Ω load.

1. <u>DC Power Consumption</u>

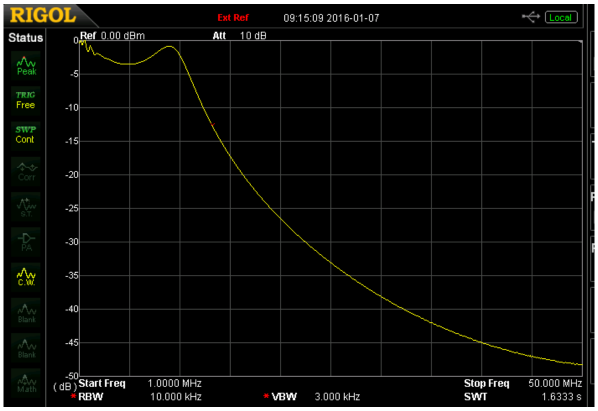
The DC input current was measured as 128 mA at a USB supply voltage of 5.02 VDC, corresponding to a power consumption of 643 mW.

2. <u>Gain</u>

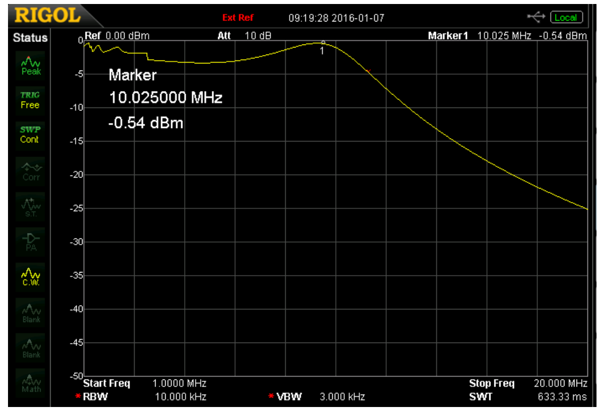
The four RF outputs had measured output levels of +6.60 dBm, +6.62 dBm, +6.66 dBm and +6.57 dBm when the PicoAmp was driven with +7.38 dBm at 10 MHz, corresponding to gains of -0.78 dB, -0.76 dB, -0.72 dB and -0.81 dB. The RF amplifiers have a nominal voltage gain of 2 to their outputs, and unity gain to a 50 Ω load. The slight additional loss is probably that of the output low pass filters.

3. Frequency Response

The frequency response of a PicoPak amplifier channel was measured with a spectrum analyzer/tracking generator as shown below. The gain at 10 MHz is about -0.5 dB and the low pass filter cuts off smoothly immediately thereafter. The attenuation at 20 MHz is 25 dB and 37 dB at 30 MHz.



PicoAmp Frequency Response 1-50 MHz



PicoAmp Frequency Response 1-20 MHz

4. Harmonics

The PicoAmp uses an LMH6609 wideband op amp that operates into a nominal 100 Ω load with ±5 volt nominal DC supplies. It is specified to have excellent x2 and x3 harmonic distortion levels of -63 dB and -57 dB respectively at 20 MHz and 2 volts p-p output swing (1 volt p-p or 0.36 volt rms actual output into 50 Ω, equal to about +4 dBm). One would expect a bit higher distortion at a +7 dBm, but that would be reduced by the PicoPak's output low pass filter. In practice, the harmonic distortion of the input signal is probably the determining factor.

The four RF outputs had relative harmonic levels as shown in the following table when the PicoAmp was driven from a low-distortion +8.0 dBm 10 MHz source via a 15 MHz low pass filter. The input had a 2^{nd} harmonic level of -60 dBc and all other harmonics were below -70 dBc.

PicoAmp Harmonic Levels, dBc				
Channel	Harmonic			
#	x2	x3	x4	x5
1	-62	-70	< -70	< -70
2	-62	-70	< -70	< -70
3	-62	-70	< -70	< -70
4	-60	-70	< -70	< -70

The unterminated output waveform is an undistorted sinewave with up to +10 dBm drive.

5. Maximum Output

The PicoAmp LMH6609 wideband op amps operate from ±5 volt nominal supplies and have a typical ±3.5 volt output swing when driving a 100 Ω load. Half of that swing appears across the 50 Ω external load, producing a maximum sinusoidal output power of 3.5 V p-p or 1.2 V rms across 50 Ω which is 30 mW or +15 dBm. The PicoAmp is specified to have a nominal 0 dB gain and to produce at least +10 dBm output. At some point between +10 and +15 dBm, one can expect the gain to drop due to saturation. The unterminated output waveform starts to show slight flat-topping at a drive level of +14 dBm.

6. Spurious Components

The most likely spurious components on the PicoAmp are those associated with its internal DC/DC converter at around 50 kHz. No evidence of such spurs was seen around the 10 MHz carrier to a resolution of about -65 dBc. A spectrum analyzer with lower noise, or a carrier crystal notch filter, would be necessary to see and quantify these spurious components. But see item #14 below for another measurement technique that can resolve the DC/DC converter spurs.

No tendency toward oscillation has ever been seen with LMH6609 RF amplifiers of this type.

7. Input Impedance (Return Loss and SWR)

The PicoPak input impedance is set by four paralleled 200 Ω terminating resistors, and can therefore be expected to present a high return loss/low SWR match. That was confirmed by measuring its input return loss with a reflection coefficient bridge along with a spectrum analyzer/tracking generator. Alternatively, the actual input impedance can be measured with vector network analyzer.

The PicoPak input return loss at 10 MHz was measured as 36 dB, corresponding to an SWR of 1.03.

8. Output Impedance

The PicoPak output impedance is set by 50 Ω series resistors at each op amp output, and can therefore be expected to present a good output match. That was confirmed by measuring the output voltage when a channel is terminated into several different values of resistive load. This method is described in Paragraph 4.8.26 of MIL-PRF-55310D, "Oscillator, Crystal-Controlled, General Specification For". That measurement is described as being made while the module is producing a normal 10 MHz output with ±10% (45 and 55 Ω) resistive terminations, but these nominal values are not critical. Suitable test loads are an unterminated 10 dB pad which has an input impedance of 61.1 Ω, and a 75 Ω load in parallel with an unterminated 6 dB attenuator which has a net impedance of 39.5 Ω. That method resulted in an output impedance value of 43 Ω, with considerable uncertainty introduced by the voltage measurements. The open circuit to 50 Ω terminated voltage ratio was 1.87 instead of the nominal 2. Broadband output impedance measurements could be made with a vector RF network analyzer with power applied to the module but no input signal.

9. Output-to-Input Isolation

The PicoAmp output-to-input isolation was measured with an RF spectrum analyzer/tracking generator by applying the tracking generator signal to the distribution amplifier output and observing the level at the common amplifier input. The dynamic range depends on that of the spectrum analyzer, and can be enhanced by using a narrow detection bandwidth and a slow sweep speed. The power applied to the distribution amplifier should not exceed its normal output level.

The measured output-to-input isolation is about 78 dB, about equal to the 80 dB dynamic range limit of the spectrum analyzer/tracking generator. It is interesting that the isolation is about 10 dB worse without power applied to the PicoAmp module, showing that some of the isolation is obtained actively.

10. Output-to-Output Isolation

Similarly, the isolation between two distribution amplifier outputs was measured with an RF spectrum analyzer/tracking generator. The output-to-output isolation was measured as 74 dB, and again was about 10 dB better with power applied.

11. Output Level versus Adjacent Channel Load

One would expect very little change in one output due to even extreme load change at another output. This property is related to the output-to-output isolation. The Channel #1 output was observed to change from +7.60 dBm to +7.61 dBm and then +7.63 dBm as the load on the other three outputs was changed from an open to 50 Ω and to a short. It is not necessary (but desirable) to terminate unused PicoAmp outputs.

12. Phase Shift Versus Adjacent Channel Load

Another practical test of the PicoAmp isolation is to observe the change in phase as measured by a PicoPak driven coherently via a PicoAmp while another channel's load is changed from an open, 50 Ω and short.

In the first such test, Channel #1 was the signal, Channel #4 was the reference, Channel #3 had the variable load and Channel #4 was terminated into 50Ω. Changing the load on Channel #3 from an open to a short resulted in a phase change of about +25 ps, with a 50 Ω termination resulting in a phase about halfway between. This test samples one of many possible cases of differential phase change versus adjacent channel load.

In the second such test, Channel #4 was again the reference, but the signal bypassed the PicoAmp. Channel #3 again had the variable load, and Channels #1 and #2 were both terminated into 50 Changing the load on Channel #3 from open to short resulted in a phase change of about +20 ps. Ω. This configuration closely resembles the use of a PicoAmp for reference distribution.

We conclude that the PicoAmp provides a high degree of immunity to phase change caused by cross-channel load change, but that it is nevertheless still important to avoid making PicoAmp load changes during a run. The best approach is to leave the reference lines connected to a group of 1-4 PicoPak modules and only change their signal inputs as different measurements are started and ended.

13. Time Domain Stability Degradation

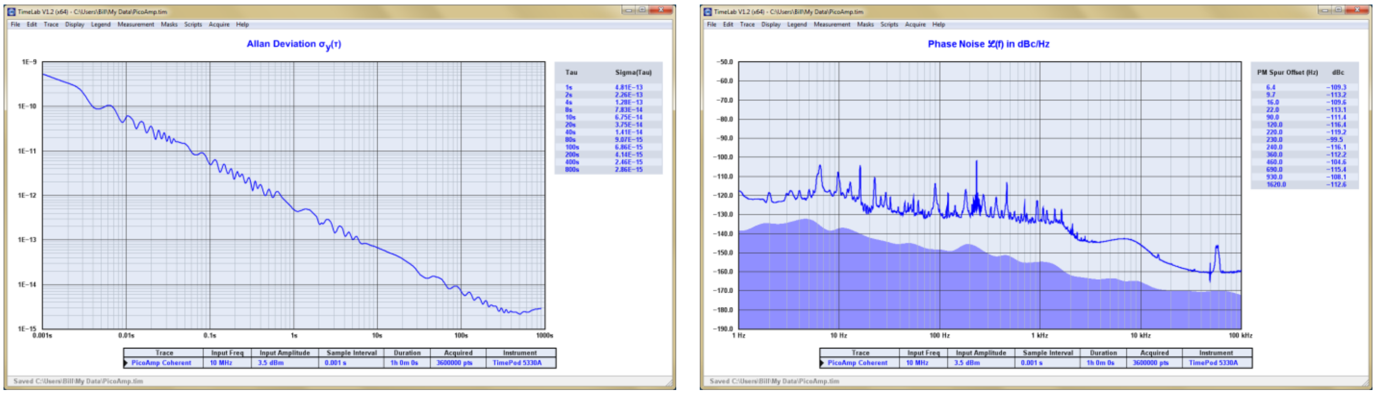
The PicoAmp LMH6609 wideband op amps are specified as having very low noise, only 3.1 nV/√Hz typical at greater than 1 MHz, so their additive noise contribution at fairly high RF signal level is quite negligible. Flicker noise contributed at low frequencies (<1 kHz) near the carrier by intermodulation is harder to predict, but previous experience with these and similar devices has been excellent.

Coherent time-domain stability runs were conducted for a PicoPak driven either via a two-way RF power splitter or via two PicoAmp channels. We assume essentially no incoherence due to the passive splitter and the possibility that the two PicoAmp channels will each introduce incoherent noise. Because the PicoPak noise floor is somewhat dependent on the drive level at its signal input, the tests were conducted at close to the same +5 dBm signal and reference levels. Other subtle factors can influence the measured PicoPak noise floor, so this test is meaningful only to the extent that no gross stability degradation is detected.

The 1-second ADEV for the case without the PicoAmp was 1.09×10^{-11}, and it was 1.10×10^{-11} with PicoAmp channels in the reference and signal paths, essentially the same noise level, and both at approximately the same signal level that produced the lowest noise floor.

14. Time and Frequency Domain Noise

The PicoAmp time and frequency domain noise was measured with a Miles Design Time Pod by passing a coherent 10 MHz signal through one channel of the amplifier. This instrument has a lower noise floor than a PicoPak, and is able to characterize phase noise in both domains.



PicoAmp ADEV and Phase Noise when operating from PC USB power

The measured PicoAmp ADEV floor is white phase noise at a level of about 4.8×10^{-13}, about x25 lower than the PicoPak, and therefore does not materially contribute to its noise.

The phase noise, while not exceptionally low, is also quite acceptable. It is mostly flat (white phase noise at about -120 dBc near the carrier and -130 dBc in the 100 Hz to 1 kHz region), and the bright lines are either from PC, are powerline related, or possibly from the rubidium oscillator test source or its switching power supply. The far-out floor is at about -160 dBc. A 10 MHz OCXO source was not significantly cleaner, and had the same noise floor, powerline components and similar spurious components. A coherent measurement without the PicoAmp amplifier had essentially the same components and a profile at the noise floor estimate in the phase noise plot. Operating the PicoAmp from an Apple iPhone charger instead of the PC was somewhat cleaner, and the noise was lower especially between 5 Hz to 10 Hz and in the 100 Hz to 3 kHz region. The spectrum was even cleaner when the PicoAmp and OCXO source were operated from a +5 VDC linear power supply. PC spurs are also likely via its USB connection to the TimePod.

The TimePod has sufficient bandwidth and resolution to show any ≈ 50 kHz spur caused by the PicoAmp DC/DC converter, but none was consistently visible down to the -155 dBc level when the PicoAmp and source were operated from the linear supply.

It is difficult to avoid or even identify the origin of the spurious components, but there is no evidence that their origin is within the PicoAmp, and, even when powered via a PC USB port, it contributes negligibly to the noise floor of a PicoPak measurement.

15. Temperature Coefficient of Phase

Under some circumstances, the temperature coefficient of phase can be the most important performance factor for an RF distribution amplifier. Phase TC can be caused by the active devices, but is more likely the result of passive components the low pass filter, and perhaps changes in the PC board material that would affect signal propagation.

The PicoAmp temperature coefficient of phase was measured by operating the module inside a small thermoelectrically-controlled heating/cooling chamber while observing the relative phase of a PicoAmp signal versus a coherent reference with a PicoPak clock measurement module.

The PicoAmp temperature was varied from +9°C to +45° and its phase varied smoothly by -115 ps and retraced well, an average phase TC of –3.2 ps/°C. This is about the same as or slightly less than, and opposite to, that of the PicoPak. If that were universally true it would provide potentially helpful compensation. In any case, it is a reasonable sensitivity.

The differential phase TC between two PicoAmp channels is also of interest, as well as the consistency of the phase TC between PicoAmp units. If the phase TC of all PicoAmps is similar, it could be partially cancelled by routing both the signal and reference through a PicoAmp. That possibility remains to be determined.

It is also of interest whether the PicoAmp TC of phase would be different and/or better without its output low pass filter, and, if so, how much the harmonics would degrade, and what the frequency response would be. Those questions will be investigated later.

16. RF Input Level Detector Threshold

The presence of RF input to the PicoAmp is indicated by an LED on the rear panel that is driven by an RF input level detector comprising a full-wave rectifier and DC level comparator. The threshold for the detector circuit to indicate an RF input was measured as +5.4 dBm. This is perhaps a bit high, and is under review.

Discussion

The PicoAmp is a fairly simple device, but one nevertheless needs to devote considerable time and effort to fully characterize it in a statistically-meaningful way. While we have only sampled those characteristics here, it is reasonable to conclude that the PicoAmp design is satisfactory for its intended purpose.

The most important PicoAmp characteristics are probably the effect of adjacent channel load impedance and temperature on its output phase. One desires that connecting or disconnecting one PicoPak does not significantly affect the measurements made by another, nor that room temperature variations materially affect the output phase, and those characteristics are largely met. Nevertheless, the best approach is to keep the PicoAmp outputs connected to their associated PicoPak modules, and to provide a stable thermal environment when making measurements.

• PicoAmp Specifications

The preliminary specifications for the PicoAmp are as follows:

PicoAmp Preliminary Specifications		
Parameter		**Specification**
Channels	#	1 input, 4 coherent isolated outputs
RF Input	Frequency	10 MHz (can be used at lower RF frequencies)
	Waveform	Sinusoidal
	Level	0 to +10 dBm (+7 dBm nominal)
	Impedance	50 ohms nominal
	VSWR	≤ 1.5:1 between 5 to 15 MHz
RF Outputs	Frequency	10 MHz
	Waveform	Sinusoidal
	Level	0 to +10 dBm (nominally same as input)
	Impedance	50 ohms
	VSWR	≤ 1.5:1 at 10 MHz
Gain	Input to each output	0 to -1 dB (0 dB nominal)
Isolation	Output-to-Output	≥ 70 dB (78 dB typical) at 10 MHz with 50 Ω terminations
	Output-to-Input	≥ 65 dB (74 dB typical) at 10 MHz with 50 Ω terminations
Noise	Time Domain ≥ 1 s	Negligible for PicoPak measurement (See plot in this document)
	Frequency Domain	(See plot in this document)
Harmonics	x2 and higher	≤ -50 dB, (≤ -60 typical, x2 largest)
Spurious Components	Non-harmonics	≤ - 80 dB (and generally much lower, depending on the power supply)
Temperature Coefficient	Phase versus Temperature	≤ 5 ps / °C (-3 ps / °C typical)
Power	Voltage	+5 VDC from USB
	Current	≤ 0.75 mA (0.65 mA typical)
Connectors	USB	Type B Male on rear panel
	RF Input	SMA Female on rear panel
	RF Outputs	4 SMA Females on front panel
Indicators	Power	Red LED on front panel
	RF Input	Red LED on front panel
Physical	Size (LxWxH)	3.28”x2.25”x1.03” (excluding connectors, feet and trim)
	Weight	≤ 5 oz (extruded aluminum case)
Accessories (Included)	Cable	5’ USB Type A plug to Type B plug with ferrite choke
	Documentation	Paper describing PicoAmp design & use

• Conclusion

The PicoAmp is a satisfactory way to distribute 10 MHz reference signals to 1-4 PicoPak clock measurement modules.

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