AM Noise in Drivers for Frequency Multiplied Local Oscillators

Neal Erickson
Astronomy Dept.
University of Massachusetts
Amherst, MA 01003 USA

Abstract AM noise on local oscillators which have been power amplified in W band are measured and compared with the needs of heterodyne receivers for the submillimeter. The noise is measured only in the 77-110 GHz range but it is shown that one may predict the expected noise that will appear in the THz output signal. In general it is found that AM noise may be low enough to be negligible for driving SIS or HEB mixers as long as the final amplifier is very strongly saturated. PM to AM noise conversion may substantially degrade the noise in some cases where strong frequency variation is seen in the response of following multiplier stages.

Introduction

Heterodyne receivers for mm-and submm wavelengths are generally based on single ended mixers which are susceptible to amplitude (AM) noise originating on their LO source. These mixers act as total power detectors as well as mixers and thus their IF output contains a term which is sensitive to the instantaneous LO power. Balanced mixers eliminate this total power sensitivity, but they are too complex to build in the submm, although this situation may change in the near future. In most receiver systems the AM noise originating from the LO is not readily measured, since there is no way to separate the LO noise from the mixer noise. In lower frequency systems highly resonant filters may be used to clean up the LO, and provide a measure of the LO noise, but these are too lossy in most cases, and they require careful mechanical tuning. In most mm-wave LO systems, InP Gunn oscillators are used as the primary LO source and these have sufficiently low AM noise that there is no need to apply additional filtering. While these oscillators must be phase locked to a low frequency reference, the properties of the reference have no effect on the AM noise (at large offset frequencies) produced by the oscillator since the phase lock loop bandwidth is generally much less than any receiver IF. Similarly the lock loop affects the phase noise only within the loop bandwidth, so the oscillator acts as a narrow band filter.

In the new generation of frequency multiplier based LO sources for THz frequencies, Gunn oscillators have too little power output to be useful as drivers, and also require mechanical tuning which is inconvenient in many applications. Herschel HIFI will use direct frequency synthesis with amplification and passive multiplication to reach frequencies as high as 2 THz. The highest frequency amplifier is within the 75-110 GHz band, where a power output of up to 300 mW may be produced using GaAs HEMT MMIC amplifiers over 10% bandwidths. Given that HIFI is intended to be wideband, it is impractical to provide any significant noise filtering at any point in the chain except near the lowest frequencies. This allows AM noise to grow enormously within the chain since there are several amplifiers involved and none of them have particularly low noise. In the WR10 power amplifiers alone there may be a gain of 30 dB. While data has been obtained in a few specific cases [1,2] showing that the noise level in such amplifiers is low enough to not significantly degrade receiver noise there has been no systematic study. This work was begun to measure the details of AM noise on the output of such an LO chain, and its behavior vs output power, particularly in the limit where the final amplifier saturates and the noise is expected to decrease.

AM and PM noise

All noise in any oscillator system may be characterized as either amplitude or phase noise. Pure amplitude noise consists of a carrier with precise frequency (as defined by zero crossings), but with a modulated amplitude. Pure PM noise consists of a carrier with precisely constant amplitude but with a modulated phase.

AM noise: $V = (1+V_n)\sin\omega t$
PM noise: $V = \sin(\omega t+\Phi_n)$
where V_n and Φ_n are noise voltage and phase terms, respectively.

Pure AM and PM noise must both have two equal sideband components, and they differ only in the relative phase of the two sidebands. AM sidebands are in phase, PM sidebands are 180° out of phase. In the case of a wideband white noise spectrum having no correlation between sidebands, the noise is exactly half AM and half PM. There is no way to distinguish AM from PM noise on a spectrum analyzer, since such an instrument does not look at the phase relationship between sidebands. Any single sideband modulation on a carrier must also be half AM and half PM. While noise may be classified as one form or the other, it may also convert between forms if there is any element which alters either the amplitude or phase relationship between the sidebands. Despite their similarity, only AM noise affects the IF noise of a single ended mixer. The phase noise influences the linewidth of the LO as far as spectral resolution is concerned but is otherwise not observable.

AM noise corresponds to simple amplitude fluctuations in a carrier, and one obvious way to reduce it is to overdrive an amplifier so that its output voltage is saturated and the output approximates a square wave. This process, of course, generates harmonics and intermodulation products, but these are all predictable and may be chosen to fall at unused frequencies. Possibly the overdrive may produce noise through other mechanisms, and saturation is not a sharp process in RF amplifiers, so the object of this study was to determine how effective this saturation mechanism is in reducing AM noise.

Since we are considering a frequency multiplier chain we must also know what will happen to a given noise level within a multiplier. In general, optimized multipliers operate at a power level where the conversion efficiency is nearly independent of input power, so they may be considered linear devices for AM noise purposes. In extreme cases the slope of the input-output characteristic may vary by a factor of two from linear, so that a multiplier may either increase or decrease amplitude fluctuations by as much as 3 dB. In spectral behavior, the input spectrum appears at the output unchanged as long as the multiplier has a flat frequency response. Multiplier behavior to phase noise is entirely different, since phase errors are due to time errors in zero crossings, and so phase noise grows as the multiplication factor squared.

AM noise measurement setup

A definition of the required noise level is needed to bound the measurements in this study. We assume that we are interested in an SIS mixer at 1 THz. The required LO power at the junction is believed to be 200 nW (-37 dBm), while the mixer noise referenced to the junction input is 2kT = 100 K (DSB). An optimum LO should add <5% to the mixer noise or 5K (-192 dBm/Hz in spectral density). This means our desired noise relative to the carrier should be below –155 dBc/Hz (DSB). If we instead consider an HEB mixer, the LO power should be less while the mixer noise tends to be higher so the LO noise may be higher as well [3]. In either case we must realize that LO power depends on many factors including junction area, so these numbers are not firm, and apply largely to devices optimized to require relatively low LO power.

The AM noise on various power amplifiers was measured with a setup shown in Fig. 1. An amplifier following a synthesizer was used to drive a single ended diode mixer in W band with a constant LO power near 1 mW. The IF noise was measured and related to the noise from the amplifier through a radiometric calibration. A test system was assembled which approximates the method to be used within Herschel HIFI to produce the LO. A 50 GHz synthesizer (HP86350L) was used to drive a 50 mW power amp in Ka band which in turn drives a tripler to WR10 band. The tripler produces 0.5-1.0 mW and drives a wideband low power amplifier boosting the level to 4 mW. Following this amplifier a variable attenuator was used to set the input level to the power amplifier under test to any needed level from 10 µW to 4 mW. Following this, a directional coupler sampled the input power to the power amplifier. Another directional coupler sampled the output power, and a variable attenuator was used to set the level going to the mixer to a constant value. The mixer was actually a fast detector (Pacific Millimeter model W-D) which acts as a single ended mixer with a wideband IF. The detector/mixer is biased with a wideband bias T, and followed by an L band IF strip with an input isolator, and a narrow band filter at 1.4 GHz to define the IF band. The mixer operated self-biased, and the bias current was measured and used to keep the LO drive constant during the measurements. Bias current was 0.7 mA for all tests, corresponding to an LO power of ~1 mW, which produced nearly the minimum conversion loss of ~10 dB.

Calibration

It is difficult to accurately measure the low level noise on an LO source due to the shot noise originating in a mixer when it is driven by an LO source. The best measure of this noise floor is to drive the mixer with a known quiet LO source but this not easy to establish. Another problem is simply establishing a power scale referenced to the input of the mixer, taking into account the conversion loss and IF gain. This is best done by using the receiver as a radiometer, although absolute power calibrations can also be done using an RF signal source and power meters. This receiver was converted to a radiometer by adding a 13 dB coupler to the mixer input and injecting the LO though the coupled arm with a feed horn on the input. The LO came from an InP Gunn oscillator, known to have very low AM noise. LO power was set at 0.7 mW and the noise temperature was measured using hot/cold loads in front of the horn. Assuming no LO noise, the 0 of input power is determined by extrapolating the IF power to 0 K input. Another way to measure the zero of noise is to turn off the LO, and measure the IF power (with the IF strip terminated in 295K by the input isolator). This presumes that the mixer produces shot noise of exactly room temperature. The difference in the input zero power measured these ways is about 200 K (referenced to the input). There is no way to readily assign this noise to either shot or AM noise, but since this corresponds to a noise level of –174 dBc/Hz, it is low enough to be neglected relative to the requirements of this study.

This hot/cold measurement was used to calibrate the receiver at all of the frequencies were data were obtained The calibration is DSB and all of the data presented here is DSB as well. For simplicity, the noise zero was assumed to be that measured with the LO off (assumed RT shot noise), which may lead to errors of as much as 3 dB in the very lowest noise measured on some sources.

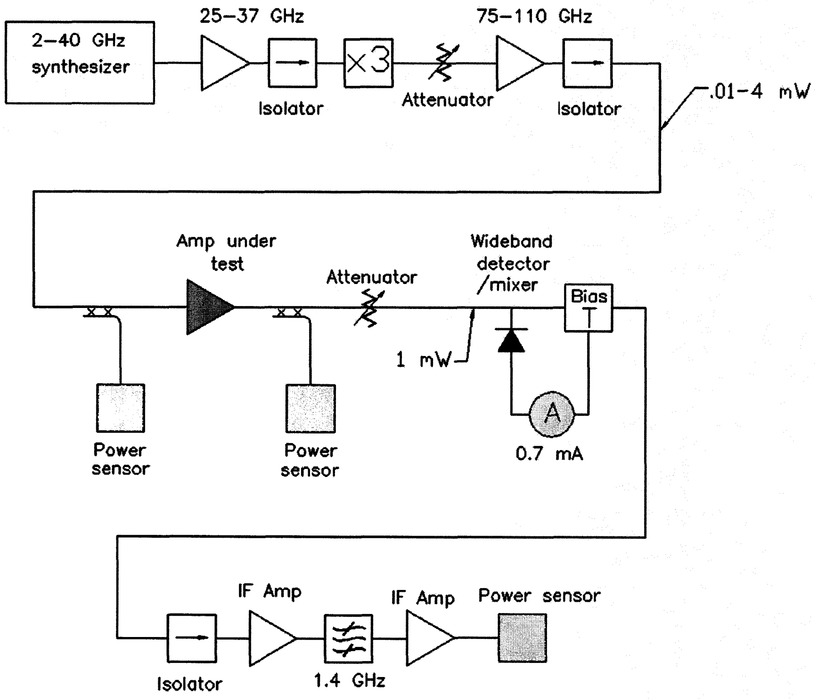

Figure 1. Test setup for measuring AM noise on an amplified LO signal.

Measurements

Several power amplifiers were measured at various frequencies to determine typical performance. All amplifiers were fabricated as GaAs MMIC's and were produced at TRW (now NGST) with designs primarily from JPL [1,4]. The first tests were of the low power driver amplifier, which was established to have AM noise below –170 dBc/Hz in the complete setup. This was necessary to be sure that it is practical to build a low noise driver using generic components, and that any noise measured would be from the power stages. The next set of power amplifiers were measured at a frequency of 77 GHz, and the data is shown in Fig 2. The small signal gain was 33 dB as can be seen from the initial slope of the input output curve. At low power this set of amplifiers shows very high noise as is expected when the carrier is weak, but the noise drops very rapidly as the power increases. For small signals the noise to carrier ratio (N/C) should drop linearly with the carrier strength, since the noise is constant. For stronger signals the N/C drops much faster than the increase in strength of the carrier as the amplifier begins to saturate. Overall an increase by a factor of three in power results in a factor of 1000 reduction in N/C so it is easy to see the great effect of saturation. At an input power near 1 mW, the N/C ratio is below –155 dBc, and so meeting the required noise is possible. It should be noted that in this test a Ka band driver amplifier was used that was very old and known to be quite noisy compared to more modern amplifiers, and yet the noise may still be made adequately low.

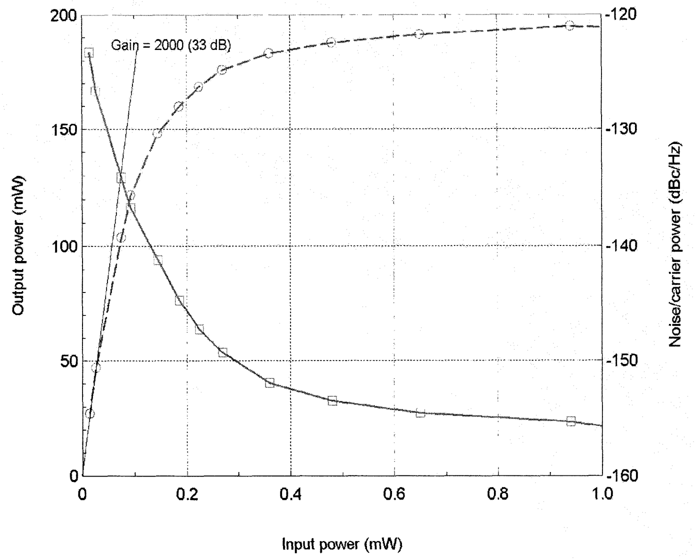

Figure 2. DSB spectral density of noise relative to carrier power for an LO signal amplified with 33 dB gain, as a function of input power to the amplifier. Output power is shown as well, with the straight line being a fit to the small signal gain. Frequency is 77 GHz.

The next set of tests was also done with the same set of amplifiers at 77 GHz, but with a lower noise Ka band driver. Results are shown in Figure 3. In these tests, the final high power stage was initially removed, and the noise of the driver amplifier was measured as well as its power output. As can be seen this amplifier never reaches strong saturation and so its noise drops rapidly up to the highest input power measured. Then the high power stage was added, and its 10 dB gain was sufficient to result in a moderate degree of saturation over the full input power range used. It is interesting to note that this amplifier produces a dramatic reduction in noise on its output as it begins to saturate, and that the output noise is less than the input over the full power range tested.. Under substantial overdrive conditions the output actually begins to decrease with input power, and the noise too increases. This behavior is typical of overdriven amplifiers but the effect is small and the noise never increases significantly.

Figure 4 shows tests on an amplifier with similar MMIC designs but assembled (at NGST) as an engineering model (EM) for the Herschel HIFI LO module [4]. The amplifier tunes 94-110 GHz with >100 mW power output, but the required band is somewhat less. The noise behavior of this amplifier is shown for two frequencies in band, one near minimum noise and the other near maximum. In both cases the noise drops to a very low level with sufficient input power and the difference appears to be just a difference in gain at the two frequencies. This amplifier was stepped across its band with 0.5 mW input at all frequencies and the variation in noise is shown in Fig. 5. This test was done at a physical temperature of 120 K as will be the case with the HIFI LO amplifiers, and the results show that there are no unacceptably noisy spots in the required band of 95-106 GHz. The ripple in noise probably arises from variations in the small signal gain due to interactions between gain stages.

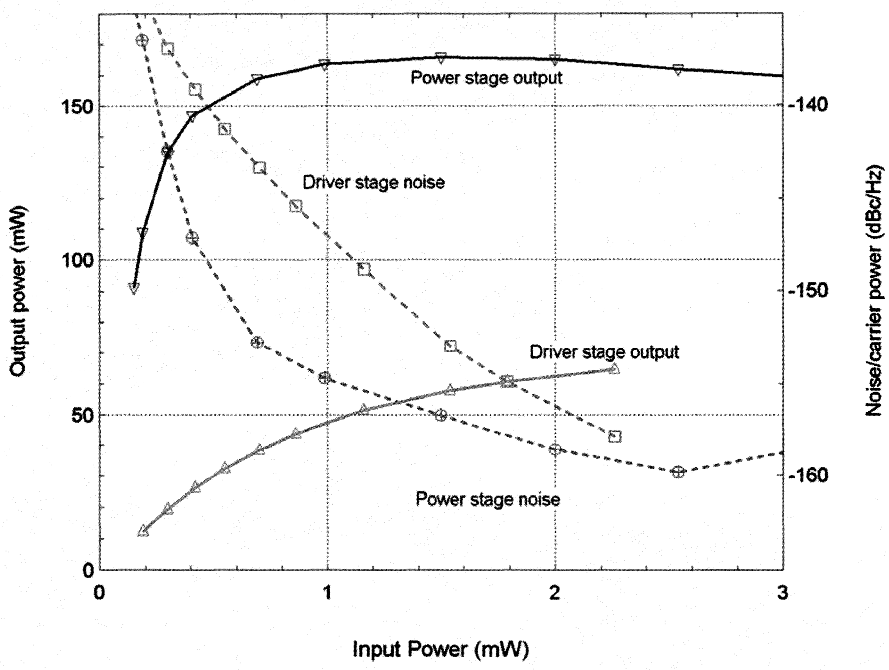

Figure 3. Output power and DSB noise/carrier ratio from a driver amplifier and high power amplifier as a function of input power to the driver amplifier. Frequency is 77 GHz and the small signal power amplifier gain is 10 dB.

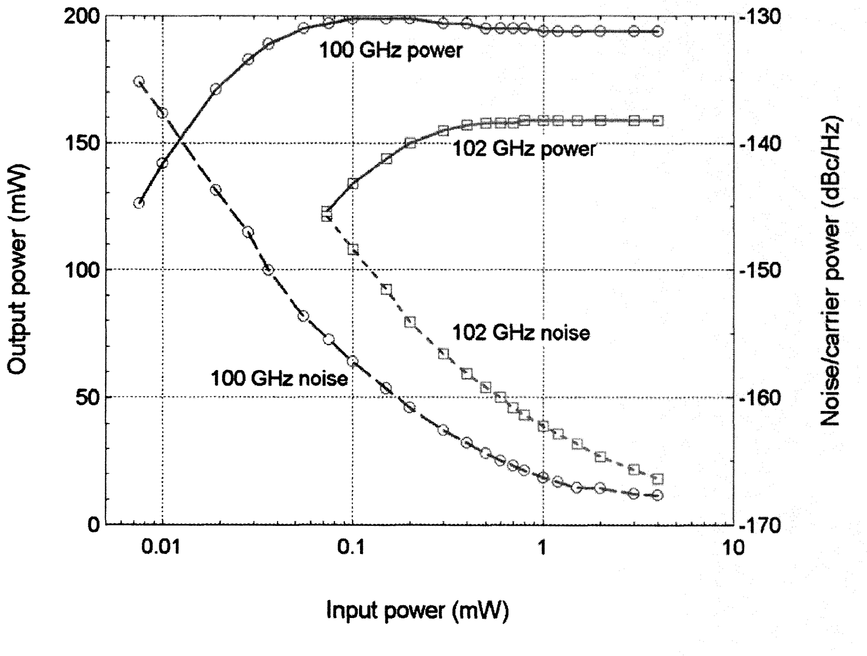

Figure 4. Output power and DSB noise/carrier ratio from a HIFI EM power amplifier at two frequencies in band representing the highest and lowest noise.

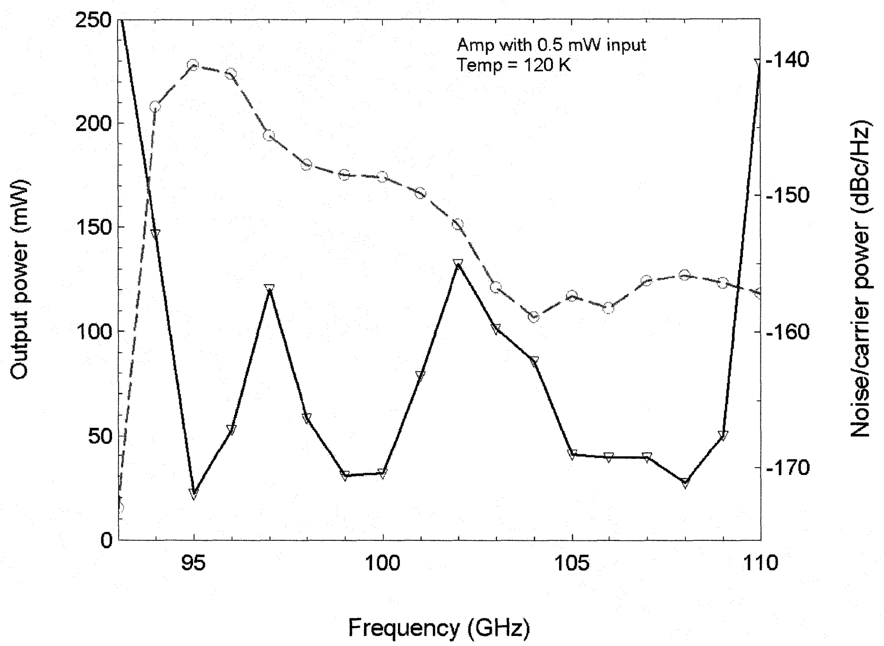

Figure 5. Output power and DSB noise/carrier from power amplifier across the full useful frequency band with a constant input power of 0.5 mW. Amplifier is operated at 120 K, as would be the case in HIFI.

Similar results were obtained with another set of amplifiers of different design at 100 GHz. All of these results show that very low AM noise may be produced through saturation of the final power amplifiers, but the required input power greatly exceeds the amount required for nominal operation. In every case the input must be at least 10 dB in excess of the small signal gain (10 dB compression), and in some cases 20 dB compression results in even lower noise. This points out that any such systems should have a large gain margin in the power amplifiers.

Power control with bias

These results show that it is not practical to control the output power of an amplifier chain by varying the input power. It is possible to attenuate the output, but such attenuators require mechanical setting, and introduce a significant loss at minimum. A better alternative is to vary the drain bias on the last power amplifier so that its saturation power varies. This will work as long as the output power drops as fast as the small signal gain of this stage, and in general the power is more sensitive to drain bias than the gain.. The results for the HIFI EM LO amplifier are shown in Fig. 6, where the power may be varied by a factor of 4 with less than a 1 V bias change, while the noise remains nearly constant over the power range. Varying the drain bias produces a very smoothly varying output power that could be incorporated into an power control loop. This same test was done on three sets of amplifiers and the results were similar

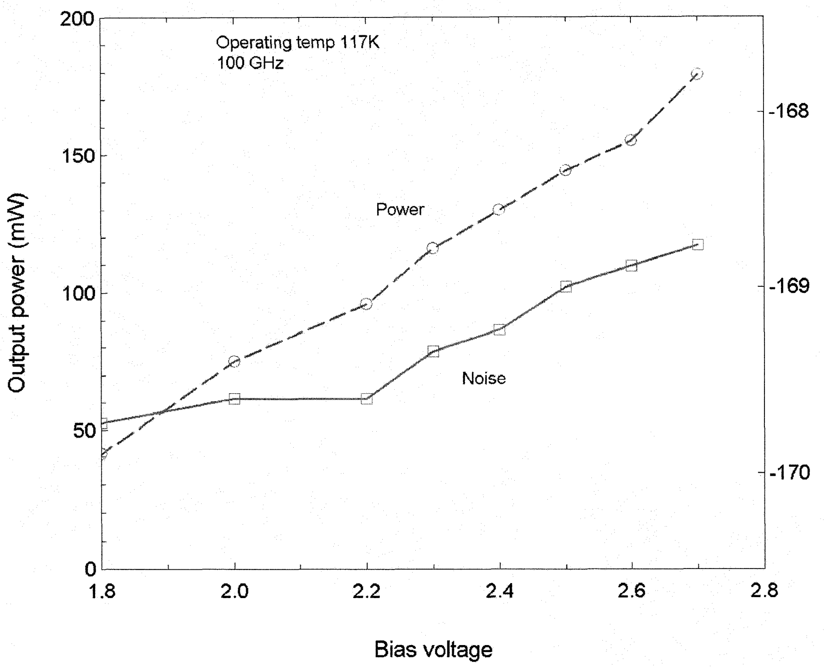

Figure 6. Power output and DSB noise/carrier from a power amplifier as a function of dc drain bias voltage on the final stages. Amplifier is operated at 117 K but similar results are obtained at room temperature.

Conversion of PM to AM noise

In any system where noise is present it may appear as AM or PM noise and may convert between them. In the highly saturated amplifiers described above, the AM noise is reduced to a very low level but the PM noise is unchanged (assuming no amplitude dependent phase shifts in the amplifier). Since conversion in later multipliers is possible it is helpful to see how large the PM noise may be. While it is not directly measured by a mixer, it is easy to convert this noise to AM using a filter which strips off one sideband. Such a filter rejects half of the input noise and converts the remainder to half AM and half PM. In the limit where the input noise is dominated by AM the output AM level would drop 6 dB, while if PM dominates then the AM level will increase to 6 dB below the input PM level. While a filter is the simplest way to measure the conversion, any gain or phase slope will have a similar (but lesser) effect, and so such conversion is likely in any system.

To measure the level of PM noise that might be present in such a system, a set of amplifiers producing low AM noise was altered by simply adding a high pass filter to their output, with the passband edge set to reduce the lower sideband by 10 dB relative to the upper, before driving the mixer as before. The before and after curves are shown in Fig. 7. In the ideal case the AM noise should drop ~6 dB with the addition of the filter, but because the filter attenuates the carrier somewhat (it is on the edge of the passband), the noise may not drop as much. What is actually seen is an 8 dB increase in noise over the upper part of the power range tested, showing that the PM noise before the addition of the filter is ~14 dB above the AM noise. In the region where the AM noise is large, the noise does drop as expected with the addition of the filter although the drop is only about 3 dB. Even in this nearly worst case situation the noise drops to an adequately low power, showing that with a good synthesizer and a reasonable choice of other components, there should be little added noise.

In a multiplier chain there are many opportunities for PM to AM conversion, given that the passband is not very flat and there may be phase dispersion as well. These are not a serious problem if the conversion occurs in the first stage but the problem becomes significantly worse if the PM noise has grown after multiplication. Fortunately the later stages are typically those with the most total bandwidth and the lowest Q so that they are less likely to suffer from rapid changes in response vs frequency.

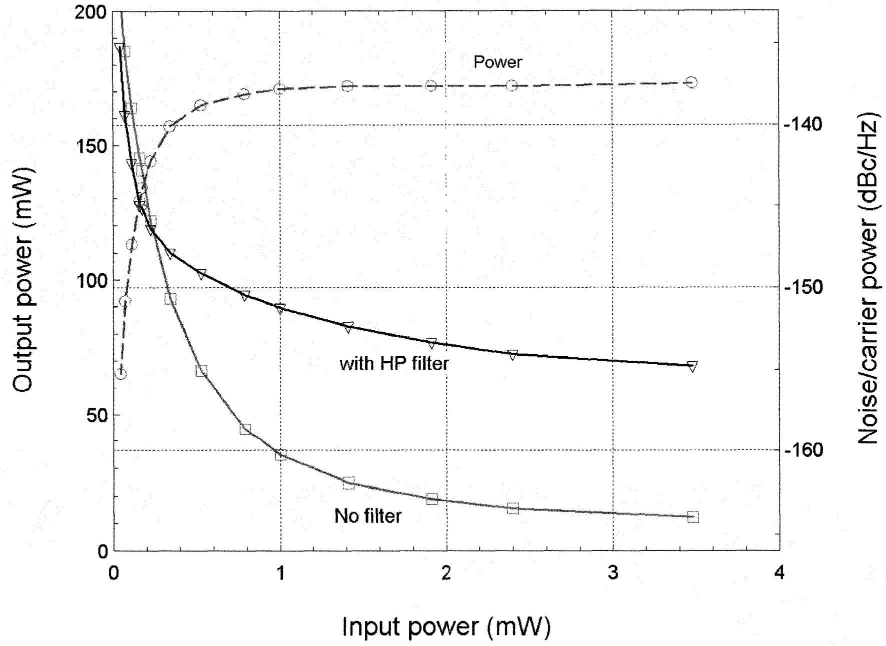

Figure 7. Output power and DSB noise/carrier for a power amplifier with and without the addition of a high pass filter with a band edge at the LO frequency. The increased noise with the filter is due to PM to AM noise conversion.

Conclusions

We have measured the AM noise on the output of GaAs HEMT power amplifiers within W-band under a range of input drive conditions. The output AM noise is below –155 dBc/Hz in all cases as long as the input is sufficiently saturated, but a very high degree of saturation is required to meet this requirement. In most cases this will require >10 dB of overdrive to reduce the noise sufficiently. It is also found that reduction of the drain voltage is a good way to reduce the amplifier output power while maintaining low AM noise.

Acknowledgement

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