Design Considerations for Amplifier-Multiplier Chain (AMC) for Low Noise Local Oscillator

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Abstract— **It is well known that broadband Amplitude Modulation (AM) noise from an Amplifier-Multiplier Chain (AMC) degrades the noise performance of a low-noise THz receiver. We have examined the role played by the source oscillator, frequency multipliers and power amplifiers in the generation of AM noise. An AMC has been designed to provide 0.2 mW of output power, tunable over 210 – 270 GHz. This module is used as the Local Oscillator for the 240 GHz SIS receiver for the Submillimeter Array. The receiver demonstrates no noise degradation with this AMC LO, when compared to operation with a Gunn oscillator based LO. Based on our experiences, we have established design rules for building AMCs for use as low-noise LO.**

INTRODUCTION

With the advent of commercial Amplifier-Multiplier Chains (AMC) operating in the millimeter and THz frequency range, the use of an off-the-shelf AMC as the Local Oscillator (LO) in low noise THz receivers becomes very attractive. In addition to the presence of low level spurious tones in the output of an AMC, these modules also present the challenge of relatively high output Amplitude Modulation (AM) noise. This AM noise is broadband in nature, covering a bandwidth, which can be many GHz wide. Thus when an AMC is used as an LO for a THz receiver, the AM noise would appear as added noise at the receiver output, increasing its noise temperature.

Starting with a discussion of the effects of AM noise, we will look at the role of 3 key components of an AMC, namely the oscillator, the diode frequency multiplier and the power amplifier, in the introduction and propagation of AM noise. We will present noise measurements on a 210-270 GHz custom built AMC that we have designed for the Submillimeter Array.

AM NOISE

THz LO modules often produce broadband noise in addition to the pure CW signal (carrier) required to pump THz mixers. At high frequency offsets from the carrier (MHz to GHz), such added noise behaves as an amplitude modulation of the carrier – AM noise. When a noisy LO operates a single-ended mixer, this broadband AM noise is down-converted into the IF, degrading the noise performance of the mixer.

Referring to Fig. 1, consider the case when the LO signal has significant AM noise within the RF bandwidth of the signal. Let T_{AM} be the effective noise temperature of this broadband noise, corresponding to a noise spectral density of $k_B T_{AM}$ W/Hz, where k_B is the Boltzmann constant. For a 1% LO coupler (or beam splitter), the mixer noise, which is referred to the optical input port, is increased by T_{AM} /100.

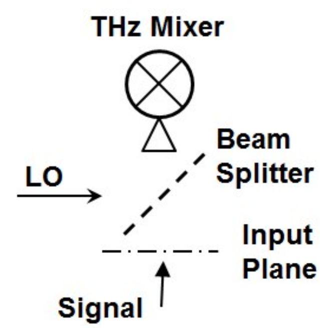

Fig. 1 Typical configuration of a THz low noise mixer in which the LO is injected optically via a beam splitter. Noise temperature of the mixer is referred to the input plane of the signal beam.

In the case of high AM noise, the noise level is conveniently described by the Excess Noise Ratio (ENR), which is usually used to measure the noise power output from a noise source. ENR is defined by the following equation:

$$\mathrm{ENR} = 10\log_{10}\left(\frac{T_{\mathrm{noise}}}{T_0} - 1\right) \qquad (1)$$

where T_0 is taken to be 290 K per IEEE standard (Haus, 1963). Thus, a noise source, with T_{noise} = 580 K, would have an ENR of 0 dB, corresponding to a noise spectral density of -171 dBm/Hz. If a source with an ENR of 0 dB is used to pump a low noise mixer through a 1% LO coupler, it would add 6 K to the receiver noise temperature.

Fig. 2 compares the measured noise temperatures of a 240 GHz receiver obtained using a Gunn oscillator-based LO and those obtained using an off-the-shelf commercial AMC as the LO. The AMC-LO introduces 10 - 25 K of additional noise. This corresponds to an ENR of 4 – 9 dB.

It may be argued that the use of a balanced mixer can eliminate the problem of AM noise from AMCs. However, besides the issue of added complexity, broadband balanced mixers typically provide only ~20 dB of LO isolation, which is comparable to the attenuation of the LO beam splitter or coupler. The main advantage of the balanced mixer is the lower LO requirement, which in turn means a potentially lower AM noise content. Clearly, low AM noise is still a necessary requirement for the LO module of a low noise receiver system even with a balanced mixer.

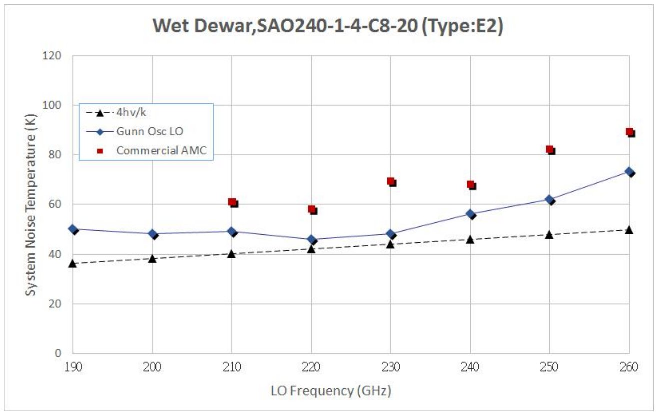

Fig. 2 Measured double-side-band noise temperatures of a 240 GHz receiver, operated by either a Gunn oscillator-based LO or a commercial AMC for a 4 – 8 GHz IF. The receiver noise is close to $4h\nu/k$ when the Gunn oscillator LO is in use.

SOURCES OF AM NOISE IN AN AMC

In order to achieve low noise operation for the 240 GHz receiver for the Submillimeter Array (Tong 2016), we have designed and constructed a YIG oscillator based AMC. This AMC is specified to provide more than 0.2 mW over the frequency range of 210 – 270 GHz. The schematic of the AMC is given in Fig. 3. Starting from the YIG oscillator operating in the frequency range of 11.6 to 15 GHz, the chain performs a frequency multiplication x18 (=x2x2x3). A single power amplifier, operating between 22 and 30 GHz, is used.

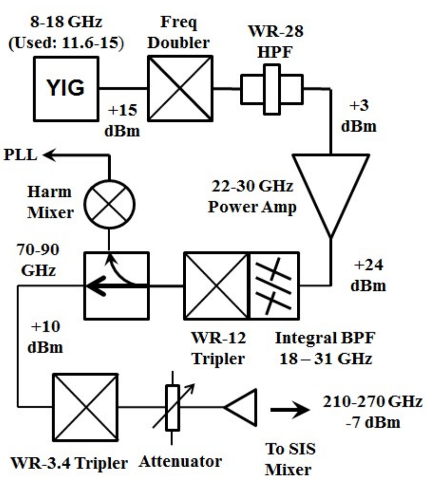

Fig. 3 Schematic of the 210-270 GHz AMC module designed for low noise operation of the 240 GHz receiver for the Submillimeter Array. The phase lock loop (PLL), essential for the interferometer, operates from the 70 – 90 GHz stage.

We have performed measurements of ENR at different stages of this AMC in an effort to trace how AM noise is generated and propagated within the module. The 3 main sources of AM noise are the YIG oscillator, the frequency multipliers and the power amplifier.

A. YIG Oscillator

Although commercial AMCs generally are not supplied with a primary oscillator, their noise output is important for the low noise operation of the AMC, as any noise from the oscillator will propagate through the AMC. YIG oscillators are chosen as the primary source in our system because they provide low phase noise needed for the interferometric operation of the Submillimeter Array.

Most solid-state oscillators incorporate integral output buffer amplifiers to boost output power and to reduce or eliminate load pulling. This amplifier is the source of AM noise at large frequency offsets from the carrier.

In order to measure the ENR emerging from the YIG oscillator, we used a narrow-band YIG-tuned filter followed by a microwave receiver to examine the noise spectral density at different offsets from the carrier. Care was taken to attenuate the output of oscillator to below the input compression level of the YIG-tuned filter. The measured ENR is calibrated using a noise source with a known ENR. The result of the measurement is given in Fig. 4 for a YIG frequency of 12 GHz. The observed ENR is ~24 dB.

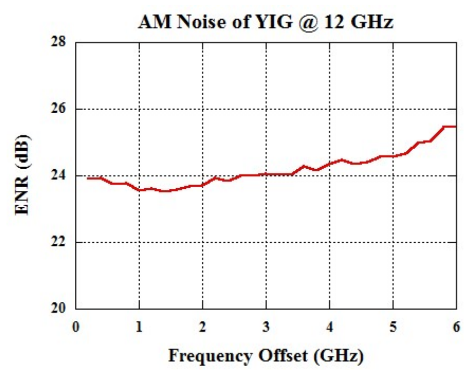

Fig. 4 Measured ENR as a function of frequency offset of the noise side-band. The YIG oscillator operates at 12 GHz and the measured noise is in the upper-side-band with frequency above 12 GHz.

The output noise temperature of an amplifier, T_{out}, is given by the following equation:

$$T_{\mathrm{out}} = G_{\mathrm{amp}} \left(T_{\mathrm{amp}} + T_{\mathrm{inp}}\right) \quad (2)$$

where G_{amp} and T_{amp} are the gain and noise temperature of the amplifier respectively, and T_{inp} is the input noise temperature to the amplifier. Assuming some typical numbers for T_{amp} and T_{inp}, we infer that the YIG oscillator used has an output buffer amplifier with a gain of ~20 dB.

Given that the oscillator output power is around +15 dBm, an ENR of 24 dB corresponds to a noise spectral ratio of -165 dBc/Hz, orders of magnitude lower than the specified phase noise level of the oscillator. If we integrate the AM noise over the entire bandwidth of the oscillator, the total amount of AM noise power is only around -50 dBm. In order to limit the impact of this broadband noise, as well as to remove any out-of-band spurious signal, any broadband oscillator should be band-limited.

B. Frequency Multiplier

As far as the propagation of AM noise is concerned, a diode frequency multiplier behaves like a frequency mixer or a frequency up-converter. This effect is illustrated in Fig. 5. An input noise sideband to the multiplier, at a frequency offset of ΔF to the carrier, appears at the output at the same frequency offset to the carrier.

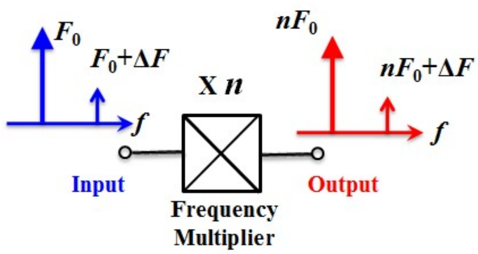

Fig. 5 Frequency up-conversion property of a frequency multiplier. A small signal side-band at a frequency offset of ΔF from the carrier at the input of the multiplier appears with the same offset at the output.

The implication of this feature is that a bandpass filter, of width B, placed at the input of a frequency multiplier yields an output AM noise bandwidth of B as well. As a result, the impact of AM noise on a THz mixer is greatest when the carrier is close to either edge of the bandpass filter. In such case, it is likely that more added noise may be observed at the IF output of the mixer to an IF of B. It has been proposed that a YIG-tuned filter, with very narrow bandwidth, can be used to restrict the AM noise bandwidth. Unfortunately, because of its relatively low power handling capacity (typically up to +10 dBm), a YIG-tuned filter cannot be placed after the main power amplifier of an AMC. Besides the maximum frequency of operation of YIG-tuned filter is 40 – 50 GHz.

We also find that the carrier-to-AM noise ratio does not seem to change much after frequency multiplication. This means that a passive frequency multiplier add only small amount of AM noise. Since the frequency multiplier presents a conversion loss to the carrier, the output ENR of the multiplier is approximately the same as the input ENR minus the conversion loss (in dB).

C. Power Amplifier

Equation (2) shows that the power amplifier is the main source of output AM noise in an AMC: not only does it amplify the input AM noise, the power amplifier also has relatively high noise temperature. It is well known that by operating a power amplifier into saturation, one can reduce somewhat the output AM noise. This is because a power amplifier has reduced small signal side band gain when it is driven beyond its compression point. We have performed measurements of the gain and output ENR of the power amplifier in our AMC. In order to measure the small signal properties of the power amplifier, a back-to-back pair of waveguide coax adapters, sized so that the carrier was 2.5 GHz below the waveguide cut-off, was used as a high pass filter to block the carrier. The measurement results are presented in Fig. 6. Just below the 1-dB compression point of the amplifier, at an output power of +23 dBm, the small signal sideband gain drops below the gain of the carrier. The ENR also starts to drop at around similar level. At the 1-dB point, the ENR has dropped by about 3 – 4 dB. When the amplifier is driven harder, at 2 dB beyond the 1-dB point (at +25 dBm output power), ENR registers a further 2 dB drop, while the small signal gain drops by close to 5 dB.

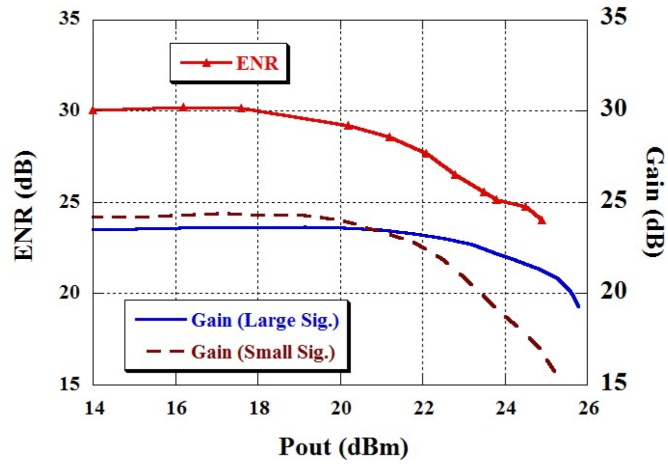

Fig. 6 Gain and ENR of the 22-30 GHz power amplifier operating at 24 GHz. The small signal gain and ENR are measured at a frequency of 29 GHz, with the 24 GHz carrier blocked by a WR-22 waveguide filter.

One may be tempted to think that a series of low gain power amplifiers, all working well into saturation would drastically limit the amount of AM noise. Nevertheless, the role of the power amplifier in an AMC is to boost the power level between 2 successive frequency multipliers. As such, the required gain is more or less fixed, otherwise one risks under-pumping the frequency multiplier following the power amplifier, leading to undesirable effects related to the generation of spurious signals. The better way is to use more efficient multipliers, which requires less power amplification in the AMC. For maximum power efficiency, we propose that the power amplifier should be operated at an output level 1 – 2 dB beyond its 1-dB output compression point.

In the case of our 210-270 LO module, the 22 – 30 GHz power amplifier is required to yield around +24 dBm to drive the next stage WR-12 tripler, with an input power of +3 dBm from the frequency doubler preceding it. Thus, a 21 – 22 dB gain at 2-dB beyond the 1-dB compression point is appropriate, corresponding to an output ENR of 24 – 25 dB, as shown in Fig. 6. Although this value appears high, the power amplifier is followed by two triplers, each with a conversion loss of about -13 dB. Finally, there is a WR-3.4 variable attenuator used to set the output power level. This attenuator further reduces the output ENR of the entire module. While we are not able to measure the output ENR directly, we believe that it is around 0 dB close to the carrier.

As discussed earlier, a 0 dB ENR would introduce a noise degradation of 6 K, which is not acceptable for an SIS receiver with 40 – 50 K noise temperature. To mitigate this problem, we have added a 4 GHz wide bandpass filter at the output of the YIG oscillator, the tuning range of which is from 11.6 to

15 GHz (a 3.4 GHz bandwidth). This filter allows us to further reduce the ENR at high frequency offsets from the carrier, such that the LO module can operate an SIS mixer with a minimum IF of 4 GHz.

PERFORMANCE OF 240 GHZ AMC

The 210 – 270 GHz AMC is designed to operate the 240 GHz SIS receiver for the Submillimeter Array. Radiation from the AMC was optically coupled to the SIS receiver through a 1% beam splitter. The module produced more than enough power (>0.2 mW) to pump the SIS mixer which has a 3-junction array (Tong 2013). As a comparison, we have also employed an LO unit based on a Gunn oscillator. To cover the entire frequency band, two Gunn oscillators were used: a 105 – 120 GHz Gunn oscillator pumping a doubler, and an 80 – 90 GHz Gunn oscillator pumping a tripler.

The double-side-band receiver noise temperature of the receiver was measured as a function of LO frequency for the AMC and the Gunn-based LOs, with the IF spanning 4 to 12 GHz. The LOs were tuned from 210 to 270 GHz. In Fig. 7, we compared the noise temperatures obtained with the two LO modules at 3 different LO frequencies as a function of IF. Clearly, the noise performance of the AMC is comparable to that of the Gunn-based LO.

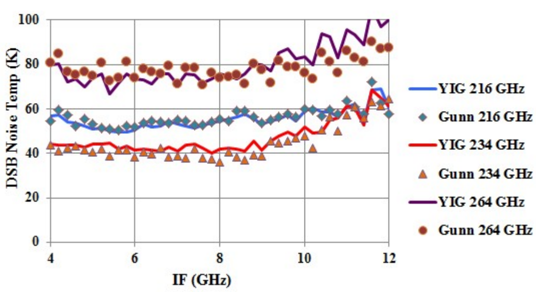

Fig. 7 Comparison of noise temperatures of SMA-240 receiver as a function of IF for 3 different LO frequencies. The receiver is either operated by the YIG-based AMC or by a Gunn oscillator based LO.

In Fig. 8, we plot, as a function of LO frequency, the difference in measured noise temperatures between the two types of LO, averaging over the IF band of 4 – 12 GHz. It can be seen that the AMC produces higher noise temperature only at the high end of the band, by ~5 K. This is a significant improvement compared to the results shown in Fig. 2. The higher noise at 270 GHz can be explained by the lower efficiency of the AMC at the high frequency end. In addition, the gain of different components of the AMC is higher at the low end of the band, which means that when the AMC operates at the very high end, noise from the lower side band is amplified more strongly by the AMC.

DESIGN RULES FOR LOW NOISE AMC

To achieve low noise performance, a number of design iterations were taken. Based on our experience, we have drawn up a number of design suggestions, which seek to minimize the output AM noise of the AMC:

1. The gain of any power amplification should be limited, and the power amplification should take place at as low frequency as possible, so that the ENR of the amplifier will be reduced by subsequent frequency multipliers.
2. For maximum power efficiency as well as optimal ENR, the power amplifier should be operated at an output level which is 1 – 2 dB below that of its 1-dB output compression point.
3. The use of higher efficiency frequency multipliers reduces the required gain of power amplification, which in turn reduces the ENR of the AMC.
4. The highest ENR occurs at frequency offsets close to the carrier because of the way frequency multipliers up-convert the noise side-bands. It is, therefore, important to have tight filtering at every stage in the AMC, particularly at the output of the YIG oscillator, which drives the AMC.

Back-to-back waveguide to coax adapter pairs can be very useful as a high rejection high pass filter, providing 90 dB rejections to unwanted harmonics as well as noise sideband only a few GHz below the waveguide cutoff.

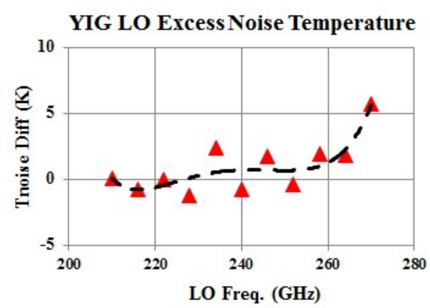

Fig. 8 Excess noise temperature introduced by AMC compared to Gunn based LO. Noise temperature is averaged over 4 – 12 IF.

CONCLUSIONS

We have studied the propagation of AM noise in Amplifier-Multiplier Chains intended for use as an LO for low noise THz receivers. The study allows us to establish basic design rules which can minimize the output AM noise of an AMC. Using these rules, we have designed a 210 – 270 GHz AMC module driven by an 11.6 – 15 GHz YIG oscillator. This module is now being used to operate the 240 GHz SIS receiver for the Submillimeter Array, demonstrating excellent noise performance, comparable to the case when the LO is replaced by a Gunn oscillator based module.

ACKNOWLEDGMENT

The authors would like to thank SAO Receiver Lab staff: Jack Barrett, Robert Kimberk and Steve Leiker for their superb technical assistance, without which this work would not have been possible.

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