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A 4-Way Quadrature Modulation Decoder using the Motorola MC13020 Chip

This document discusses how to use the MC13020 chip to decode other modes besides C-QuAM. Those other modes are QuAM, Independent Sideband (ISB), and Compatible Independent Sideband (C-ISB), an independent sideband mode that uses cosine amplitude correction built into the MC13020 chip to maintain envelope compatibility as it does for C-QuAM.

Before we proceed into how this is done a good history of DSB + Carrier, Envelope Detectors, C-QuAM, and C-ISB QuAM, ISB, and Synchronous Detectors is in order and why these four two channel modes are similar and what makes this easy to do with the MC13020 chip. While the other Motorola AM Stereo chips are capable of the C-ISB mode they are not really adaptable to operate in synchronous ISB mode.

§ DSB + Carrier – Double Sideband with Carrier. This is the simplest method of modulation only requiring rectification with a simple diode to convert the envelope of the signal to the audio baseband. It is very inefficient in that only up to half of the transmitted energy is in the sidebands while the other half is always dedicated to the carrier. This is the case for Mono AM, C-QuAM, and C-ISB. Instead of developing the BFO in the receiver to demodulate the signal and in which all the transmitted energy would be in the sidebands the carrier is sent along with the modulation to be the BFO robbing the transmitter of half its power, power that could be dedicated to the modulated signal for abetter signal to noise ratio and much less power usage.

§ Envelope Detector – This type of detector is the simplest of all detectors but requires that all information be in the in-phase channel and none in the quadrature channel for distortion free reception. This also requires that the information in the upper and lower sidebands maintain their proper phase and amplitude characteristics in relation to the carrier. During skywave, selective fading, and multi-path conditions these relationships can become distorted and the coherent information that once was only contained in the in-phase channel can now be found in the quadrature channel. Interfering signals from other stations and natural sources are incoherent in relation to the desired carrier and produce information in both the in-phase and quadrature channels of the desired signal and will produce the same kind of distortion known as “quadrature distortion.” This is the inherent weakness in the signal's envelope in which this detector demodulates.

§ Synchronous Detector – This type of detector does not require a carrier other than the purpose of having the BFO that controls it is frequency locked to the carrier. This is what makes it synchronous because the phase angle of the BFO is synchronized at a certain angle with the carrier. This detector only demodulates the signal for the channel that the BFO driving it and is phase-synced to, be it the in-phase, quadrature, or somewhere in between and completely eliminates the channel 90° away from it. Since it ignores the channel 90° away from it it is immune to quadrature distortion and this also allows for two channels to be transmitted on one carrier known as QuAM while only occupying the same bandwidth as a DSB mono transmission.

§ QuAM – Quadrature Amplitude Modulation is an amplitude modulation mode that allows the transmission of 2 different signals on the same carrier. One of its widespread uses is the transmission of the color information along with the black & white information of an analog color television signal for both the NTSC and PAL and their numerous variations. This was done in suppressed carrier mode. There is no carrier at all to demodulate the signal but a short burst of a carrier signal without modulation during retrace for the PLL that controls the BFO to lock onto. These are two carriers on the same transmission frequency but are separated by 90° as in Sine & Cosine i.e. when sine is 0 then cosine is 1 and vice-versa. This allows the two signals to be separated and demodulated with synchronous detectors that are driven by a BFO that is frequency and phased locked to the reference signal via a PLL circuit. In the case of color TV this is the color burst signal and for AM radio it is the carrier. For QuAM detection very little carrier is need to allow enough for the PLL to lock onto. As little as ⅛ the power required for envelope detection is sufficient for PLL locking.

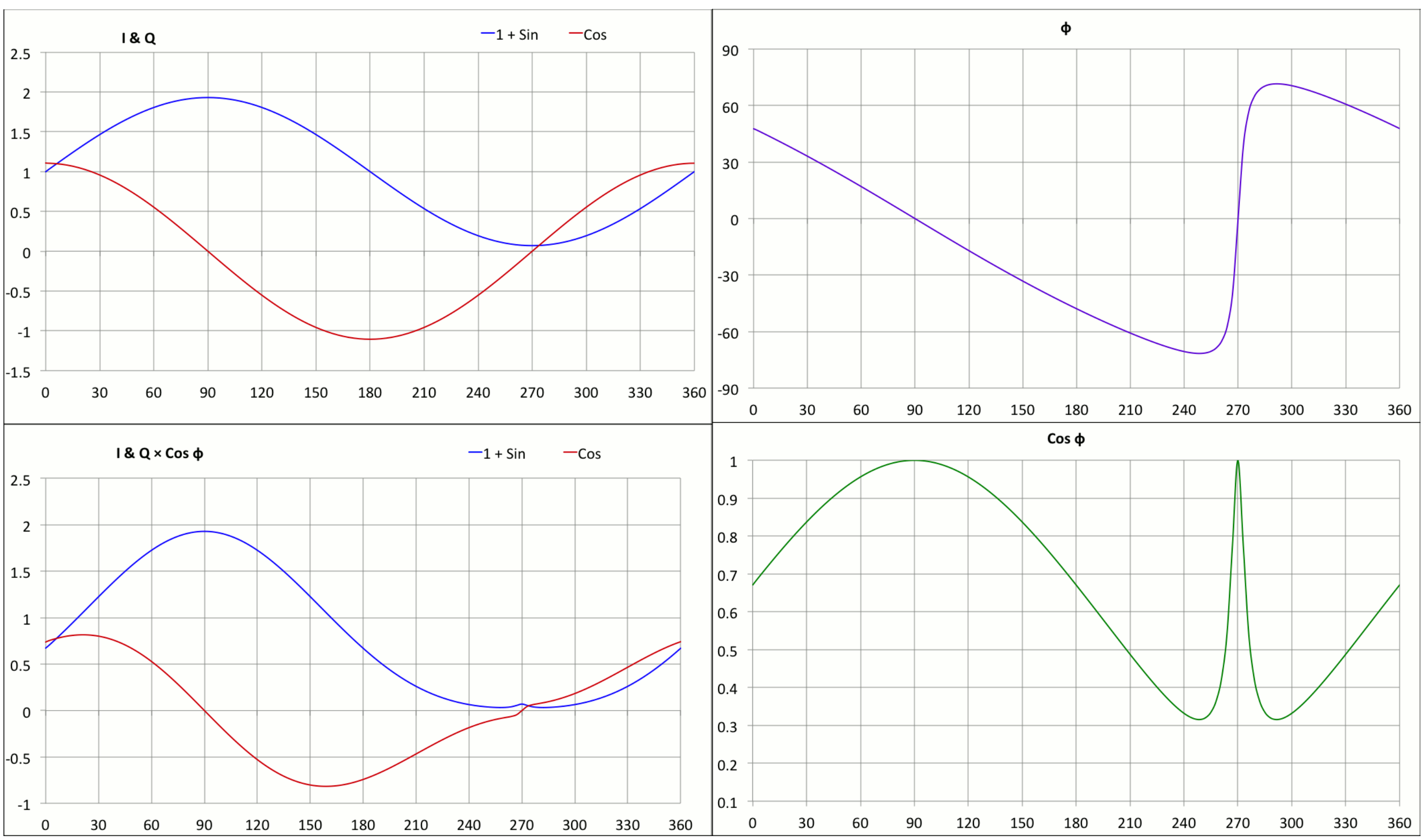
NOTE: Throughout this document the terminology of I & Q along with [1+]L+R & L–R are used, where I & Q are the two channels and [1+]L+R & L–R in regard to AM Stereo is the content modulating them respectively.

§ ISB – Independent Sideband is a mode in which the two signals transmitted are separated by frequency and not by phase as it is in a QuAM signal. QuAM modulation is used to generate an ISB signal but the audio is phase encoded in a way to cause one of the sidebands to be nulled per channel. After the audio is matrixed from L & R into L + R & L – R it is audio phase shifted to produce a 90° differential phase shift between the matrixed channels. This produces sidebands generated from (L+R) w/f@0° & (L – R) w/f@+90° modulating the I & Q modulators and after summing they produce the distinct L & R channels in the lower and upper sidebands respectively. Through trigonometric proofs this can be demonstrated. In its simplest definition: Let A=audio and C=carrier, then $USB = \cos(A) \times \cos(C) + \sin(A) \times \sin(C)$ & $LSB = \cos(A) \times \cos(C) - \sin(A) \times \sin(C)$. During good signal conditions via ground wave there isn't much difference other than a 3dB reduction in noise and as background noise increases this provides a slight benefit. Where ISB really excels is when the transmission path via skywave and/or multi-path distorts the signal by introducing non-linear phase and amplitude effects within the passband of the signal and ISB has the best immunity out of all the other modes. With a non-ISB QuAM type of signal when the natural amplitude and phase relationship of the two modulations as they are distributed in both sidebands is compromised channel separation is reduced and under more severe skywave effects this produces noticeable audio phasing effects and even signal nulling. With co-channel interference where the interfering signal causes the PLL to mis-track a QuAM signal will suffer from channel mixing and platform motion where the dominant signal content will bounce between the two channels at a frequency rate that is the beat frequency of the desired and un-desired carrier. With ISB this PLL mis-tracking error can occur but since the signals are separated by frequency and not by phase, each channel is contained within its own sideband, and there is no special amplitude and phase relationship between both channels and sidebands as they are in a QuAM signal so the signal can't be compromised in this manner. For ISB during PLL mis-tracking and selective fading during skywave phasing effects play themselves out in a much less severe form and in most cases phase distortion within the audio passband of the signal caused by moderate PLL phase mis-tracking is not readily noticeable to the human ear. It is the differential phase distortion between upper and lower sidebands that produces signal nulling in a DSB or QuAM signal similar to a comb filter. A perfect example of this is a guitar phaser effect. Within these circuits the guitar signal is separated into two paths where one path is phase shifted in which the phase is also slowly modulated and mixed back in with the original signal to produce a differential phase mixing.

§ 'C-' as in Compatible – For both QuAM and ISB, in which QuAM can be used to generate ISB, quadrature information is created along with the existing in-phase information. For a DSB mono signal both upper and lower sidebands have both I & Q components but their special phase relationship causes the 'I' component to be reinforced for the envelope and the 'Q' component to be canceled out. When both modulated I & Q components are present in a DSB signal where a phase modulation term in generated the envelope is defined as $Env = \sqrt{(1 + I)^2 + Q^2}$ and a phase component is generated as $\phi = \tan^{-1}[\, Q / (1 + I)\,]$ and thus the envelope is also defined as $Env = (1 + I) / \cos\phi$. This is not equal to $1 + I$ and will produce distortion for envelope detectors. To make a QuAM type signal compatible for envelope detectors the modulated carrier amplitude is multiplied by $\cos\phi$ thus making the envelope equal to $1 + I$. This is what Motorola calls C-QuAM or Compatible Quadrature Modulation and since ISB is also generated using QuAM the 'C-' in C-QuAM can also be applied to an ISB signal creating C-ISB by applying the audio phase shifting process as described in the previous paragraph on ISB to the input signal of a C-QuAM exciter. The most convenient place to do this is inside the C-QuAM exciter but it that isn't possible then matrixing L & R into L + R & L – R, applying the differential 90° audio phase processing and then de-matrixing them back into L & R before sending them to a C-QuAM exciter is the other way. Given the available equipment e.g. existing C-QuAM exciters, with the addition of the differential 90° audio phase processing this is the easiest way to generate an ISB type signal which is also compatible with envelope detectors.

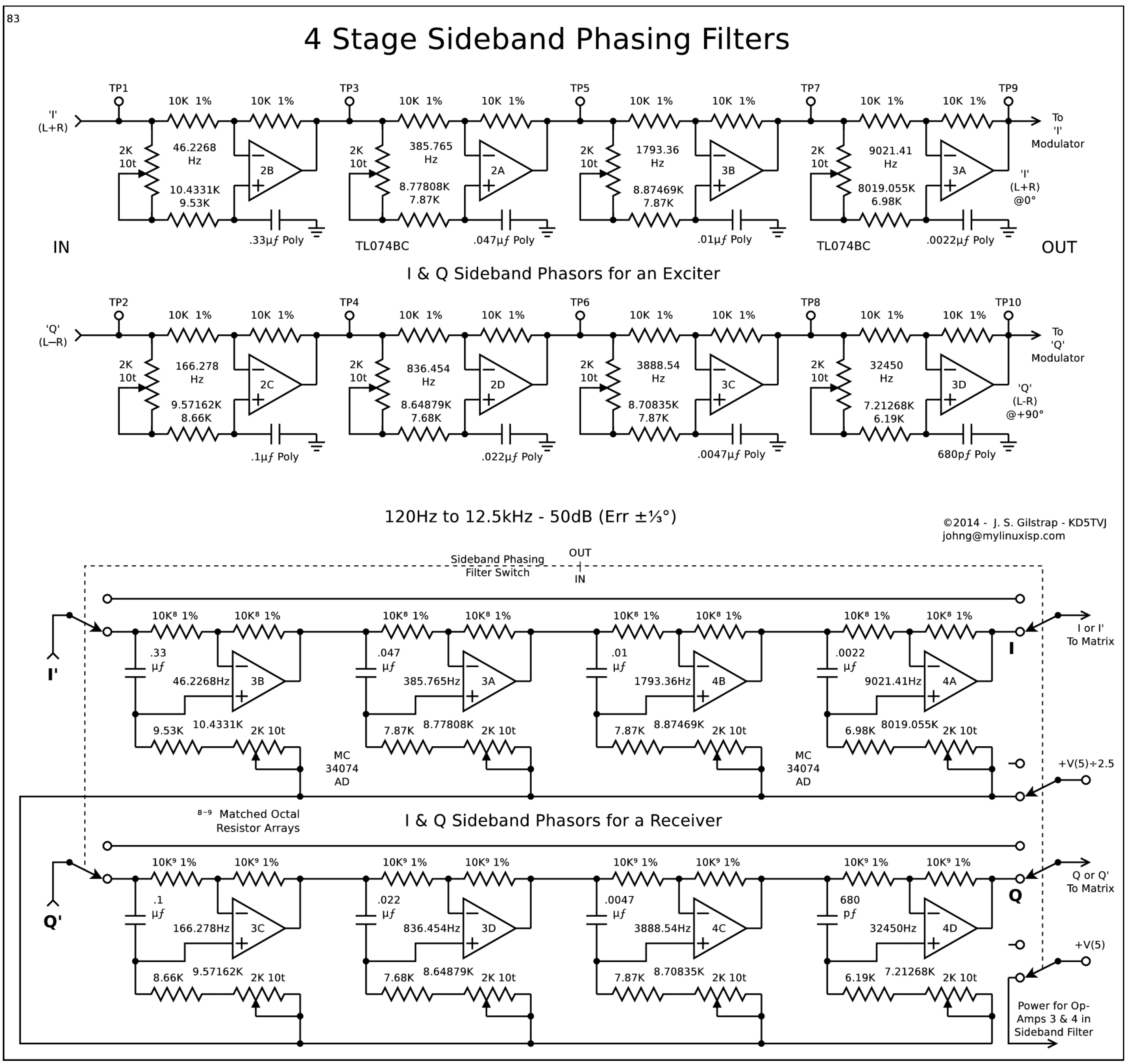
§ C-ISB – The benefits of ISB over QuAM also apply to C-ISB but the characteristics of an ISB signal don't stop there for a cosine corrected envelope compatible signal but also enhance the distortion correction circuit's performance in the decoder under less than optimal conditions because of the unique relationship of the instantaneous positions of the I & Q vectors and the phase angle of them. For a QuAM signal during single channel modulation both I & Q modulating signals are at their zero crossings or are peaking. For the 'I' channel during the peaking phase of -100% modulation the 'I' channel is at 0 because the 1+ carrier is fully canceled by the -1 value of the modulating 'I' signal but the 'Q' channel is at 1 producing a phase angle of ϕ=90° and Cosϕ=0. When the envelope is remodulated with 'I' for compatibility there is nothing left of the 'Q' channel for the decoder to recover during the distortion cancellation process which would require a gain of ∞. To keep things tame C-QuAM has a single channel downward modulating limit of the 'I' channel of -75% with an ~72° of peak phase deviation to keep the modulation levels acceptable for the decoder. During decoding the distortion cancellation circuit produces a maximum gain of ~3 which keeps distortion cancellation within acceptable limits especially during light interference but is still vulnerable to large inaccuracies during heavier amounts of interference and skywave distortion. When S/N drops below 21dB C-QuAM starts expanding the noise. With an ISB signal the audio phasing converts all cosine waves in the 'I' channel to sine waves in the 'Q' channel during single channel or stereo modulation. This has the unique effect on the instantaneous values of the I & Q vectors. When the modulating signal for the 'I' channel is -1 and cancels out the carrier to produce -100% modulation the modulation of the 'Q' channel is at 0 so the effective phase is 0°. At +100% modulation the same is true also. The peak phase deviation of ~72° doesn't occur until single channel modulation of the 'I' channel reaches -95% modulation, on par with levels of modulation of the 'I' channel from a mono only signal, a 26% increase or +2dB over C-QuAM under these conditions. Since the phase is approaching 0° during strong downward modulation it takes a much stronger interfering signal to push the gain of the distortion correction amp past its normal limits and out to ∞ compared to C-QuAM thus making C-ISB more immune to the effects of interference.

Here are some graphs showing I & Q vectors, phase, and cosine correction for C-ISB.



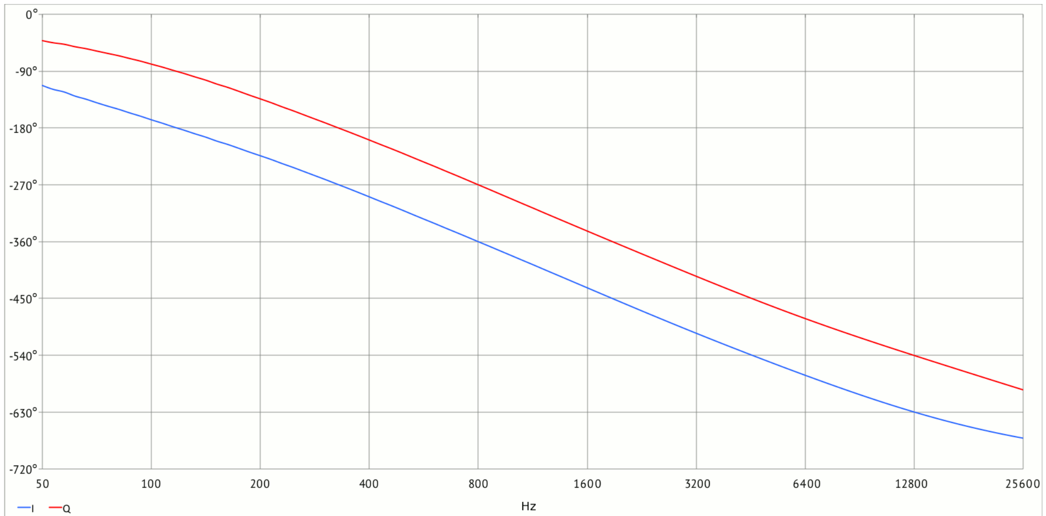
In the top left graph are the I & Q vectors for regular ISB modulation. In the bottom left are the I & Q vectors for C-ISB after cosine correction has been applied to an ISB signal. In the top right is the phase deviation for both ISB & C-ISB. In the bottom right is the gain reduction applied to an ISB signal to create C-ISB using cosine correction. As you can see in the bottom left graph only moderate distortion is generated during cosine correction as compared to the one above. If this was C-QuAM the distortion would be more severe completely inverting the peak of the 'Q' channel returning it to zero during negative peak modulation of the 'I' channel. When a C-ISB signal is synchronously detected as ISB much less distortion is produced than what would be when C-QuAM is synchronously detected as QuAM, in fact a C-ISB signal detected in this manner without cosine distortion correction would produce vary favorable results when interference would make cosine distortion correction errors undesirable. What we have with C-ISB vs. C-QuAM is that cosine distortion correction holds up much better under the same level of interference and when interference gets too bad then C-ISB has less distortion when synchronously detected as ISB.

§ Audio Sideband Phasing Filters – In the drawing below are the phasing filters for [C-]ISB. These are 4 stage phasers that have a ±⅓° phase deviation from 90° and a theoretical -50dB opposite sideband suppression capability. These are best used for High Fidelity ISB Stereo with a 50Hz to 15kHz audio response. Its -50dB attenuation covers a range of 120Hz to 12.5kHz and at 100Hz and 15kHz it still has a fairly respectable -35dB suppression for stereo programs. For the exciter the phasers are phase lagging while the ones for the receiver are phase leading. If the exact same frequencies used in the exciter are used in the receiver then the ±⅓° phase deviation from 90° is also negated for a 0° phase error correction thus returning the modulating signals to their original phasing and separation before transmission. To produce a 90° phase difference between the I & Q modulation signals in analog mode a running phase shift is needed. At the lower and upper end of the range ~59°/oct. is produced while in the middle it is ~73°/oct. This rolling phase shift has the benefit of shifting harmonic peaks off their fundamentals reducing p-p values for a given signal level thus allowing a louder signal to be modulated for the same p-p level. Whether to use phase leading in the exciter and lagging in the receiver contrary to what is previously stated would depend on which would produce the greatest reduction in p-p value for a given signal level on most program material during . In the digital

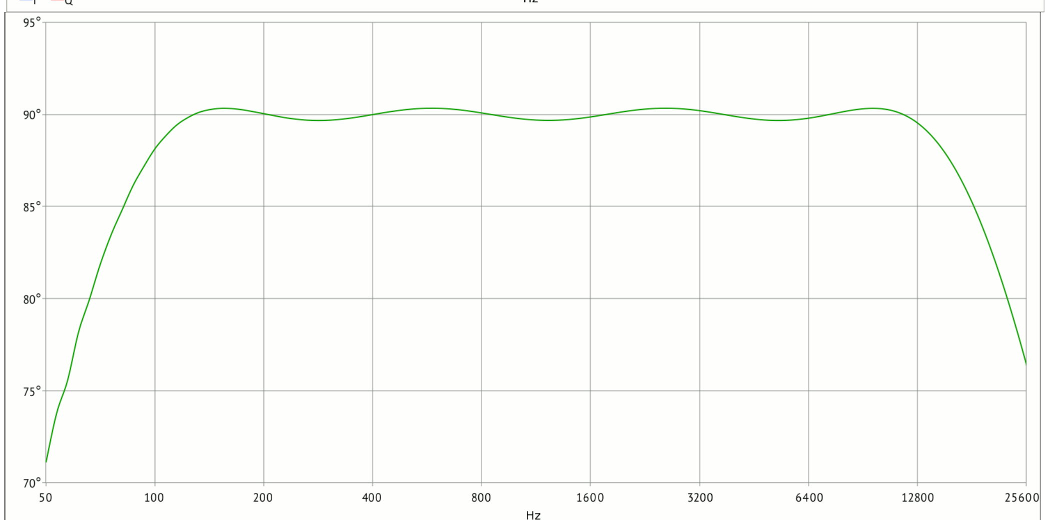


domain just applying a Hilbert transform to the 'Q' channel only would not produce this effect but might be detrimental to 'Q' channel peak levels e.g. a square wave. For best results high quality polystyrene capacitors should be used.

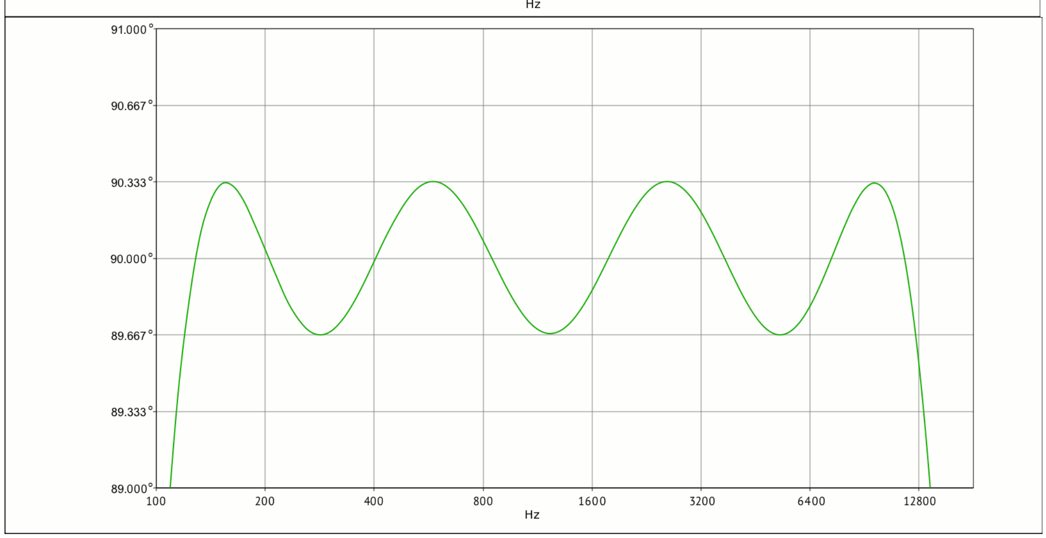
In the drawing above there are test points TP1-TP10 in the exciter phaser section. These test points are there to calibrate each phaser within the array at its defined frequency. Using a function sine wave generator with an optimum 6 digit frequency accuracy set it to the desired frequency for the phaser to be calibrated. Inject the signal into the array at the input and place a quadrature phase detector on the test points associated with the input and output of the phaser section to be calibrated. Adjust the phaser until the output of the phase detector is zero. Repeat this for the remaining nine sections using their defined frequency. Running a full frequency sweep with the phase detector by connecting it to the final output of the I & Q phaser arrays and injecting the signal into both inputs is a good way to check for accuracy and perform fine tuning if necessary. Test points are not present in the phaser array for the receiver but this same process can be used to calibrate them also.



Rolling phase shift for both I & Q channels showing Q leading I by 90°.



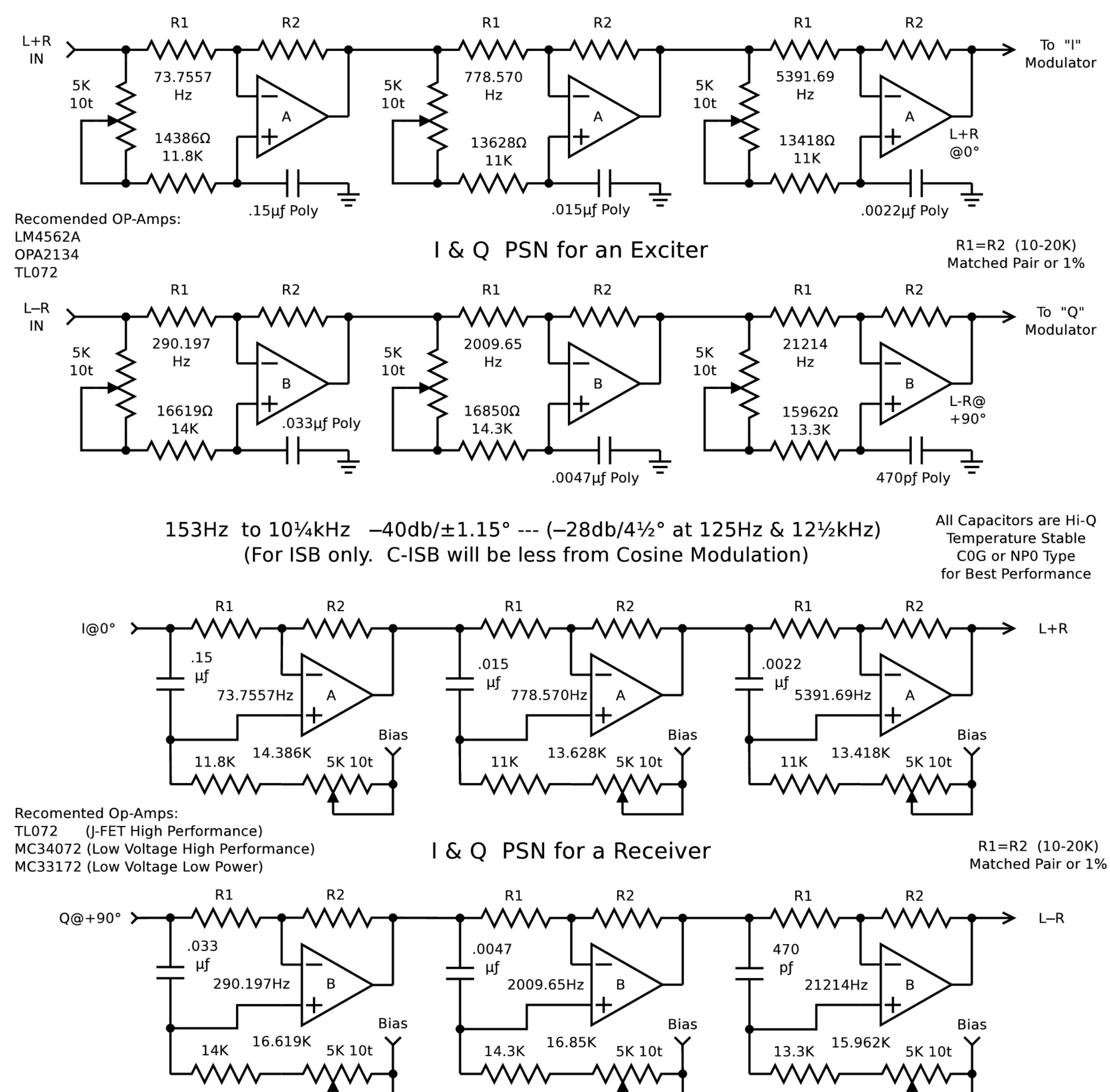
Phase differential from 50Hz to 25.6kHz.



Phase differential close up showing ±⅓° accuracy.

A slightly more economical version but with less phase accuracy is in the drawing below and is suitable for medium fidelity. It covers the audio range from 153Hz to 10¼kHz with a maximum phase error of ±1.15° providing a minimum opposite sideband suppression of -40dB. It has a rolling phase shift of ~47°/oct. at either end and in the middle it is ~58°/oct. This covers the standard 10.2kHz upper frequency range used for most AM transmission masks. It still has a somewhat respectable suppression level for most stereo programs of -28dB at 125Hz and 12½kHz. This is probably best suited for most applications today but if a 4 stage one is used for transmission and a 3 stage is used for reception or vice-versa then a maximum of ±1.478° phase error correction will result reducing minimum separation recovery to -37.8dB. While the 3 stage version has less phase accuracy it is still well suited and very adequate for C-ISB since cosine correction has a much greater detrimental effect on sideband suppression especially if 'Q' channel levels are not increased on average by 1.5dB before transmission. This also helps improve separation for receiving C-ISB with a two radio approach tuned to upper and lower sidebands. On the next page are two graphs, one is the sideband attenuation graph and the other is a ±1.15° phase differential close up between the I & Q channels. Deciding on whether to use a 3 or 4 stage unit is up to what the highest transmitted frequency response is. Standardizing on one or the other for both exciters and receivers will ensure complete phase reversal in the receiver as if no phasing were ever used as in straight [C-]QuAM A great benefit if either/or both channel(s) is/are used for digital information.

3 Stage Phase Shift Networks



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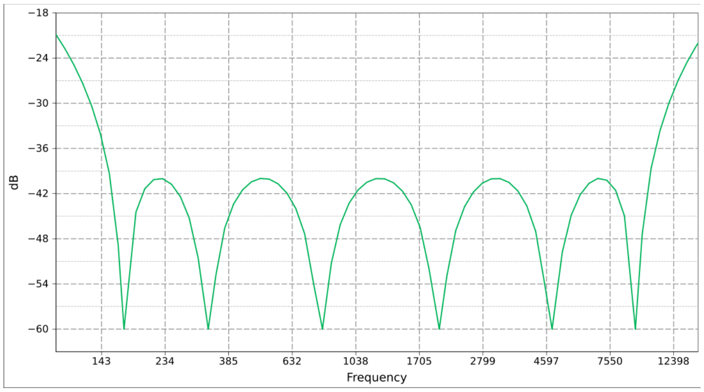
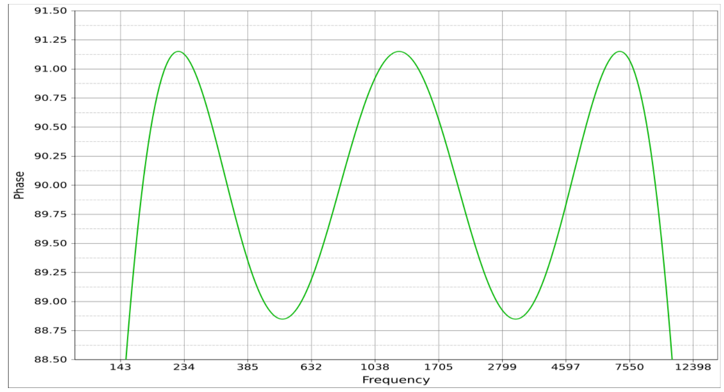


Sideband Attenuation Graph



Phase differential close up showing ±1.15° accuracy.

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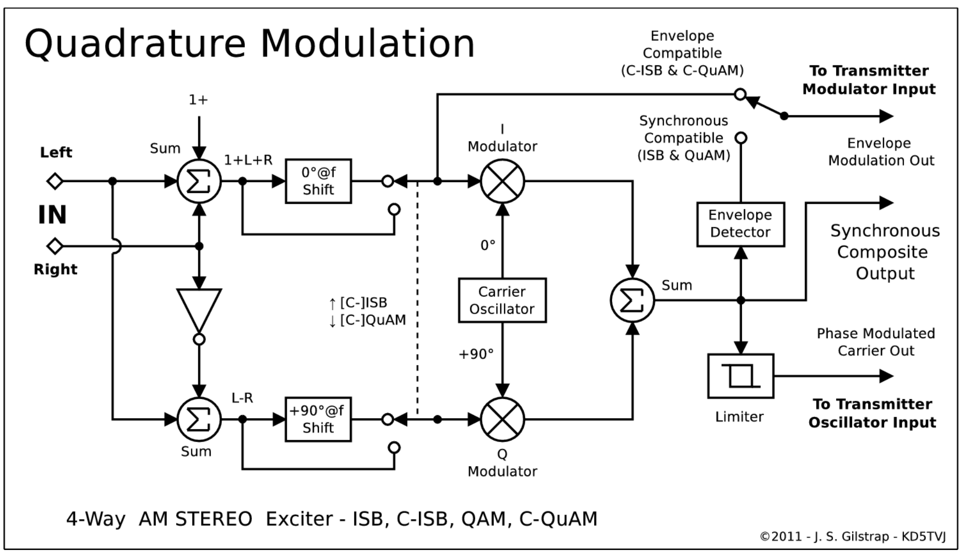
§ 4-Way Exciter – This is a block layout and very simplified version of an exciter that could transmit these four different systems. As far as what is available for 'Compatible' mode are the numerous C-QuAM exciters and for 'Synchronous' mode the Harris STX1 exciter and maybe their STX1A that is a converted STX1 for C-QuAM that could be made into a 4-Way exciter.



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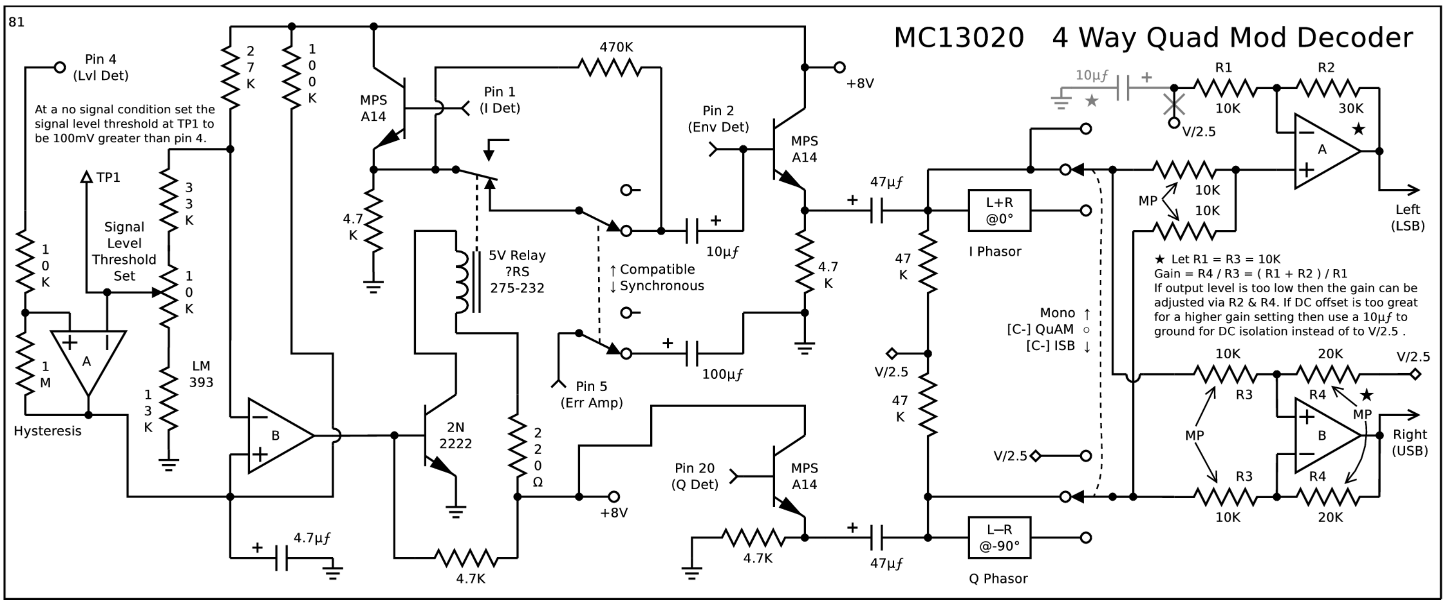
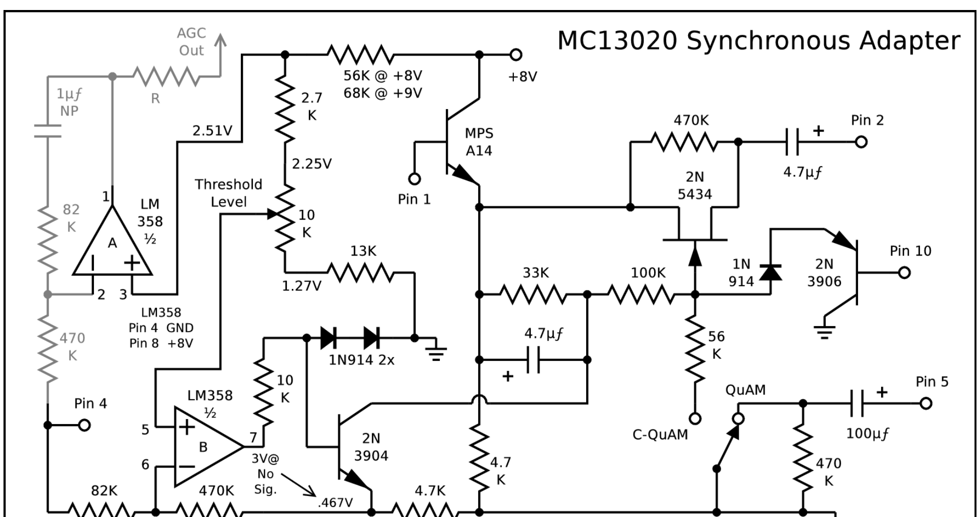
§ Using the MC13020 Chip – This chip has the most versatility for operating in other modes besides C-QuAM. While the MC13022 and the MC13122 do have pins for the 'Env', 'I & Q' detectors and makes for an easy interface for using sideband phasing filters there is no way to disable the 'Err Amp' as there is on the MC13020 so as to operate in pure synchronous mode without cosine distortion correction. This chip series offers some very desirable features that make the MC13020 limited in its capability. If this 2 generation chip along with its improved AMAX brother the MC13122 had the cosine correction disabling feature then this would make the MC13020 obsolete for synchronous detection. The MC13028 chip will always preform cosine correction and is the least desirable out of all since the availability synchronously detected signals are non-existent.

To obtain the Env, I & Q signals from the MC13020 the signals need to be buffered first as the output impedance is 4.3K and along with the detector capacitor this forms the lowpass filter for each detector. It is recommended that these three capacitors be changed to .001μf to optimize phase matching between the three detectors especially for [C-]ISB. Buffering is done with an emitter follower using an MPSA14 darlington transistor. The signal to the 'I' phaser array is taken from the Env Det and for synchronous mode the buffered signal from the buffered (low impedance) I Det is is used to drive the un-buffered (high impedance) Env Det. This will not hurt the chip as all detector pins are connected to a 4.3K resistor and a collector output of a Gilbert cell synchronous detector while the other end of the resistor is connected to V+. This connection is switch operated and through a signal level detector it is disconnected when the signal level is too low; when the PLL is out of or has the chance of going out of lock. A more complex signal detector circuit could also include a window detector on the low pass filtered Q Det and/or the PLL loop filter voltage. The switching is done by a mechanical reed switch but a low resistance switching FET with a low cutoff voltage or a C-MOS analog switch could also be used. Driving the Env Det with the buffered I Det also allows the internal matrixing to still operate and produce a fully synchronously detected stereo signal at both Left & Right outputs (pins 7 & 8) where automatic stereo/mono switching is still pilot driven. There is also a mechanical switch to manually select envelope or synchronous mode which also disables the Err Amp from performing cosine distortion correction. For both the signals going to the I & Q phaser arrays they are DC filtered to provide the correct bias voltage for the phaser arrays. It is defined as +8V/2.5 or 3.2V which if using any of the MC3407x low voltage high performance series op-amp this is optimal. This op-amp is unique as common mode input range includes Vee like an LM324 but has the performance of a JFET TL072 op-amp however its noise voltage and current are $32nV/\sqrt{Hz}$ and $220fA/\sqrt{Hz}$. A TL072 vs $18nV/\sqrt{Hz}$ and $10fA/\sqrt{Hz}$ and a NE5532A is $5nV/\sqrt{Hz}$ and $700fA/\sqrt{Hz}$. If the signal strength is not strong enough for good s/n then another op-amp could be used and the bias voltages adjusted appropriately. If the 3 stage phaser arrays are used then 2 quad op-amps (MC34074) could be used with the two left over to de-matrix I & Q into Left/LSB & Right/USB. To select from Mono, [C-]QuAM, or [C-]ISB a manual switch is used but 2 quad analog switches driven by logic could also be used with the 2 switches left over to preform Env/Sync mode switching instead of the 2N2222 and the reed switch.



Here is a version of the synchronous adapter part that uses a blend to QuAM feature using a FET. Although this version does not have the sideband phasing filters it can replace the switched version above; everything left of the 47µƒ capacitors except for the MPSA14 buffers for the 'Q' & 'Env' channels and their associated emitter resistors.

Both of these are better suited for DTR that mute the audio somewhere later in the audio path while tuning. If used on a mechanically tuned radio an additional window detector on the 'Q' channel or PLL loop filter will help prevent a false lock action while tuning.



This is an automatinc blend to QuAM version that will transistion over a ~100mV change in the signal level at pin 4. There is a threshold level set to adjust for optimum performance. For starters it should be set at a no signal condition with pin 7 on the LM358 op-amp at ~3V which should have the FET fully turned off. The FET should have a cutoff voltage of <3V and an RdsOn of <50Ω. The other half of the op-amp can be used for an optional AGC amp that has infinite DC gain so detected signal level will remain constant while the RF/IF AGC gain is still within the normal operating range. The op-amp output has a 0 to 6.3V range so choose 'R' so the AGC gain in the RF/IF amps is not overdriven. The RF/IF amps must have a positive gain coeffecient i.e. an increase in voltage produces an increase in gain. If this half of the amp is not used then pins 1 & 2 should be connected.

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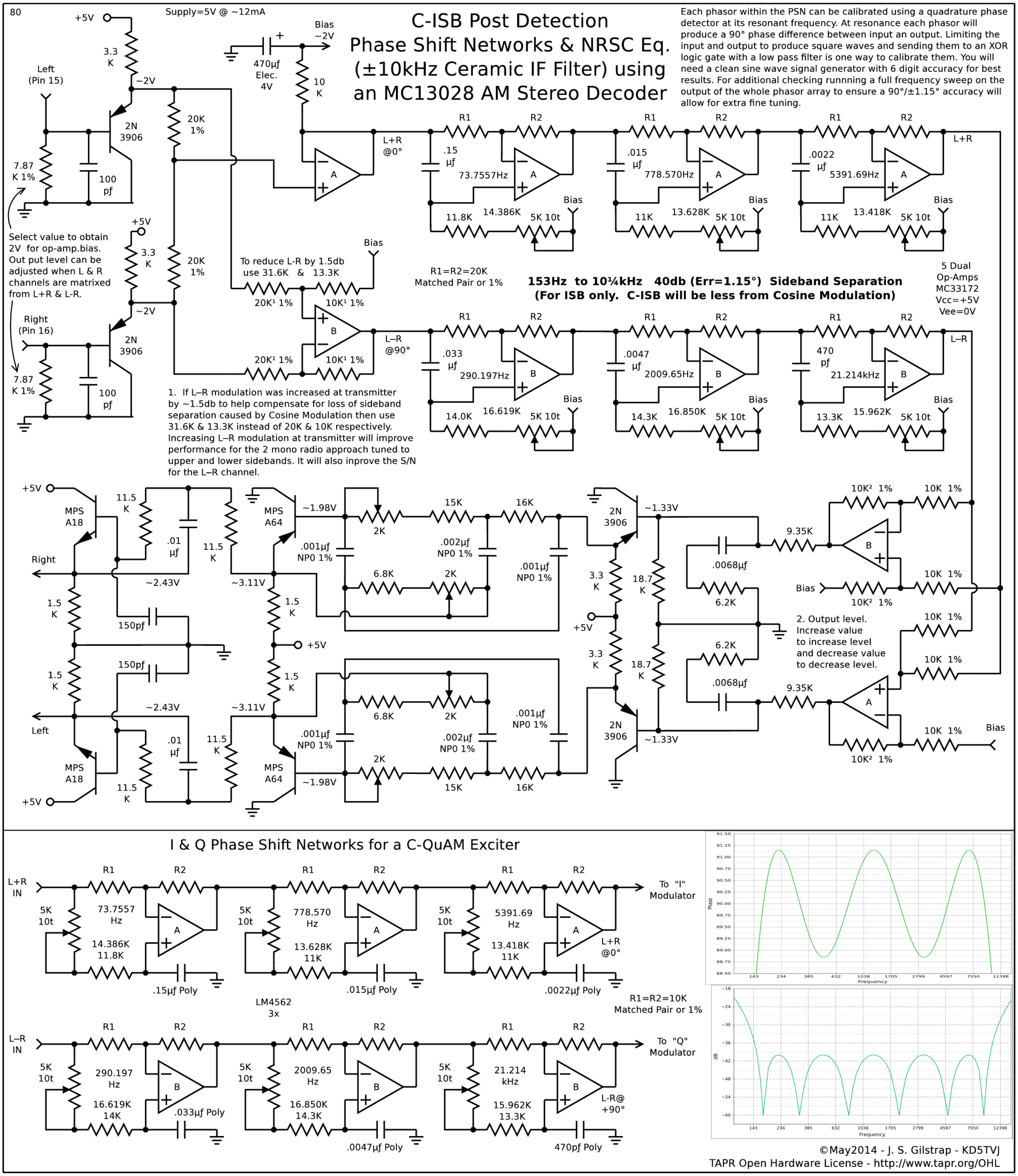
§ Using the MC13028 Chip – This chip is the 3rd generation chip that has better immunity against producing distortion during detuned conditions. It also deals with platform motion better but whether this is as much a benefit while running it in C-ISB mode or a hinderance since ISB signals are fairly immune from PLL phase mis-tracking remains to be seen.



To obtain I & Q signals since the chip only has Left & Right outputs requires that Left and Right be matrixed into I & Q requiring 2 buffer transistors and 2 extra op-amps. After the sideband phaser processing and de-matrixing the circuit has 10kHz adjacent carrier whistle filters which are twin-T high-Q notch filters, and low pass filters which provide high frequency boost around 11.5kHz to help boost the upper end response. There is also a partial de-emphasis filter and in combination with an RF bandwidth of 15kHz, a ±10kHz ceramic filter, and the HF boost LPF this should approximate a 75µS de-emphasis with an 8.7kHz pole out to at least 10kHz. These post detection filters using transistors are buffers/source followers and could be replaced with bootstrapped op-amps. These filters can also be applied to the MC13020, MC13022 & MC13122 although the '22 series already has notch filters built in and are not necessary.

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