Design of a Ka Band RF Front End for Single Target Tracking Radar

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Abstract:

Single Target Tracking Radars are primarily used for fire control application. Ka band (26.5GHz-40GHz) is a good choice for Radar system engineers for these types of Radars. In this paper, we present difficulties and challenges involved in designing a low noise Ka band RF Front End for STT Radars which use monopulse target tracking.

Keywords - ***Fire Control Radars, Super Heterodyne Receiver, LNA, Noise Figure, STC, LO, BPF, Receiver Protector.***

I. INTRODUCTION

Tracking low flying targets with high angular accuracies using a relatively smaller antenna for illuminating the targets, demands use of Radar operating frequencies typically in Ka Band and above. This is most common in Single Target Tracking Radars (STT) for fire control applications. Very narrow beam width is essential for this type of applications to meet the angular accuracy requirements. The narrow pencil beams also help in mitigating multipath problems while tracking low flying targets. Monopulse technique is usually employed in tracking radars because of its high angular accuracies, resistance to target scintillation and immunity to jamming. Availability of wide RF bandwidth at Ka band and above also provides added advantage in Electronic Counter - Counter Measure (ECCM).

Increase in atmospheric attenuation at higher frequencies restricts the range of the Radar. At the same time, the Radar has to meet the requirements e.g. accuracy, size, weight, power etc. This makes Ka band Radars suitable for short range, high resolution Single Target Tracking (STT).

Receiver is one of the major sub-systems of any Radar. The function of a receiver is to receive weak target echoes from antenna, amplify them sufficiently, filter out unwanted signals and down-covert the input RF signal to a frequency which can be given to Signal Processor (SP) for extraction of target information. A Radar receiver typically has two major parts, RF Front End and Down-conversion receiver. The RF Front End is the most sensitive part of the receiver as it determines overall Noise Figure of the system, provides initial amplification, prevents complete receive chain from damage and filter out unwanted interfering signals. The Down-conversion stage performs one or more down-conversion of the RF signal and brings down the frequency to an Intermediate Frequency (IF) suitable for the Signal Processor. This stage also provides required amplification, selectivity, measures for phase and gain matching etc. Therefore, design of the RF Front should be carried out carefully to meet the Radar system requirements.

In this paper, we present various design aspects and architecture of a Ka band RF Front End. Section II describes selection of receiver architecture. Section III describes two stage receiver architecture with sub-harmonic mixing. Section IV describes architecture and design of the Ka band RF Front End. Concluding remarks are provided in Section V.

II. SELECTION OF RECEIVER ARCHITECTURE

The capabilities of receivers are highly dependent on the type of receiver. There are many types of receivers that are commonly used e.g. crystal video receiver, TRF receiver, homodyne receiver, super-heterodyne receiver etc. As most of the Radars require Doppler frequency information, demodulation of the RF signal must be carried out through frequency mixing process. This restricts the receiver to be either a homodyne or a super hetero-dyne type of receiver.

In homodyne receivers, the RF and Local Oscillator (LO) are identical, which are fed to a mixer. These types of receivers are also known as direct conversion receivers. The homodyne receivers show poor sensitivity, poor interference suppression and less dynamic range compared to the super-heterodyne receivers. But these receivers do not have any image frequency issues as there is no IF.

Super-heterodyne receivers are the most used receiver architecture especially for Radar applications. Input RF is mixed with LO frequency to generate an IF. If the RF is very high, two or three down-conversion stages are used to bring down the RF to final IF, which is easy to process by SP. Bulk of the amplification and filtering is carried out at IF stages. Frequency tuning is achieved by varying the first stage LO, thereby keeping the IFs constant. The main drawbacks associated with the super heterodyne receivers are rejection of image frequency and inter modulation products at each mixer stage. As the super heterodyne receiver architecture is selected for the Ka band receiver, selection of all the IFs and LOs are done carefully to achieve better image rejection and inter modulation rejection.

Throughout the paper, we have considered Ka band RF input frequency as 35-36 GHz and final IF frequency of 120 MHz. We have considered two approaches to down convert the Ka band RF signal into the final IF. The first approach employs three stage down conversion whereas the second approach employs two stages of down-conversion.

Advantages and disadvantages of both the approaches are discussed in the following section.

1. Three Stage Down-conversion Architecture

In this architecture, Ka band RF input signal is down-converted to X-band fixed frequency IF signal (IF1) using a variable Local Oscillator (LO) signal. The IF1 is down-converted to IF2 at L-band and finally, the IF2 is down-converted to final IF (IF3) at VHF frequency. The simplified block diagram of the three stage architecture is shown in Fig. 1.

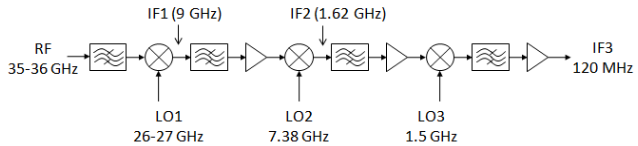

Fig. 1 Architecture of a three stage down-converter

Spurious analysis [1] is carried out for each of the mixing stage to finalize the LO and IF frequencies. The spurious analysis of the first mixing stage is shown in Fig. 2. In the first mixing stage, there is a range of RF frequencies (34.5-36.0 GHz) that can generate IF1 as a result of 5th order inter-modulation (3*LO-2*RF). There is another inter-modulation product of 7th order (3*RF-4*LO) that lies outside the RF bandwidth. For the 5th order in-band inter modulation product, the first mixer must be selected with excellent 5th order inter modulation rejection characteristics. The 7th order spurious rejection will be generally high for any mixer. Moreover, RF filter ahead of the mixer will provide additional rejection, as it lies outside the RF bandwidth.

LO Frequency Range:	26	to	27	GHz
IF Frequency Range:	9	to	9	GHz
Desired M (RF Harmonic) Value:	1			
Desired N (LO Harmonic) Value:	-1			
Spurious Response Search Range:	33	to	38	GHz
Full RF Frequency Range:	35	to	36	GHz

I. M (RF Harmonic) > 0, N (LO Harmonic) < 0

M \ N	1	2	3	4
-1	35.00 - 36.00	17.50 - 18.00	11.67 - 12.00	8.75 - 9.00
-2	61.00 - 63.00	30.50 - 31.50	20.33 - 21.00	15.25 - 15.75
-3	87.00 - 90.00	43.50 - 45.00	29.00 - 30.00	21.75 - 22.50
-4	113.00 - 117.00	56.50 - 58.50	37.67 - 39.00	28.25 - 29.25

II. M (RF Harmonic) < 0, N (LO Harmonic) > 0

M \ N	-1	-2	-3	-4
1	17.00 - 18.00	8.50 - 9.00	5.67 - 6.00	4.25 - 4.50
2	43.00 - 45.00	21.50 - 22.50	14.33 - 15.00	10.75 - 11.25
3	69.00 - 72.00	34.50 - 36.00	23.00 - 24.00	17.25 - 18.00
4	95.00 - 99.00	47.50 - 49.50	31.67 - 33.00	23.75 - 24.75

Desired RF Response	User Input Cells
Spurious Responses (Inside Search Range)	Spurious Responses (Inside RF Band)

Fig. 2 Spurious analysis of first mixing stage

In second mixing stage, there is no nearby input frequency to the mixer that can generate IF2 as inter-modulation products. However, there are two input frequencies to the mixer i.e. 8.19 GHz and 9.3 GHz that can generate IF2 as result of 4th (2*RF-2*LO) and 7th order (4*LO-3*IF) inter-modulation products respectively. These two frequencies can be easily suppressed using a band pass filter ahead of the second mixer in addition to the rejection available in the mixer for these inter-modulation products. Spurious analysis of second mixing stage is shown in Fig. 3.

LO Frequency Range:	7.38	to	7.38	GHz
IF Frequency Range:	1.62	to	1.62	GHz
Desired M (RF Harmonic) Value:	1			
Desired N (LO Harmonic) Value:	-1			
Spurious Response Search Range:	8	to	10	GHz
Full RF Frequency Range:	9	to	9	GHz

I. M (RF Harmonic) > 0, N (LO Harmonic) < 0

M \ N	1	2	3	4
-1	9.00 - 9.00	4.50 - 4.50	3.00 - 3.00	2.25 - 2.25
-2	16.38 - 16.38	8.19 - 8.19	5.46 - 5.46	4.10 - 4.10
-3	23.76 - 23.76	11.88 - 11.88	7.92 - 7.92	5.94 - 5.94
-4	31.14 - 31.14	15.57 - 15.57	10.38 - 10.38	7.79 - 7.79

II. M (RF Harmonic) < 0, N (LO Harmonic) > 0

M \ N	-1	-2	-3	-4
1	5.76 - 5.76	2.88 - 2.88	1.92 - 1.92	1.44 - 1.44
2	13.14 - 13.14	6.57 - 6.57	4.38 - 4.38	3.29 - 3.29
3	20.52 - 20.52	10.26 - 10.26	6.84 - 6.84	5.13 - 5.13
4	27.90 - 27.90	13.95 - 13.95	9.30 - 9.30	6.98 - 6.98

Desired RF Response	User Input Cells
Spurious Responses (Inside Search Range)	Spurious Responses (Inside RF Band)

Fig. 3. Spurious analysis of second mixing stage

In third mixing stage also, there is no frequency nearby to the mixer input frequency that can generate IF3 as inter-modulation products. However, there are few input frequencies that can generate IF2 as result of 4th, 5th, 6th, 7th and 8th order inter-modulation along with the image frequency. All of these input frequencies to the third mixer can be easily suppressed by using a band pass filter ahead of the mixer. Spurious analysis of third mixing stage is shown in Fig. 4.

LO Frequency Range:	1.5	to	1.5	GHz
IF Frequency Range:	0.12	to	0.12	GHz
Desired M (RF Harmonic) Value:	1			
Desired N (LO Harmonic) Value:	-1			
Spurious Response Search Range:	1	to	2	GHz
Full RF Frequency Range:	1.62	to	1.62	GHz

I. M (RF Harmonic) > 0, N (LO Harmonic) < 0

M \ N	1	2	3	4
-1	1.62 - 1.62	0.81 - 0.81	0.54 - 0.54	0.41 - 0.41
-2	3.12 - 3.12	1.56 - 1.56	1.04 - 1.04	0.78 - 0.78
-3	4.62 - 4.62	2.31 - 2.31	1.54 - 1.54	1.16 - 1.16
-4	6.12 - 6.12	3.06 - 3.06	2.04 - 2.04	1.53 - 1.53

II. M (RF Harmonic) < 0, N (LO Harmonic) > 0

M \ N	-1	-2	-3	-4
1	1.38 - 1.38	0.69 - 0.69	0.46 - 0.46	0.35 - 0.35
2	2.88 - 2.88	1.44 - 1.44	0.96 - 0.96	0.72 - 0.72
3	4.38 - 4.38	2.19 - 2.19	1.46 - 1.46	1.10 - 1.10
4	5.88 - 5.88	2.94 - 2.94	1.96 - 1.96	1.47 - 1.47

Desired RF Response	User Input Cells
Spurious Responses (Inside Search Range)	Spurious Responses (Inside RF Band)

Fig. 4 Spurious analysis of third mixing stage

The main drawback of the triple down conversion architecture is that the SWaP (Size, Weight and Power) factor is high. The cost and reliability is also less compared to the architectures employing less number of down conversion stages.

2. Two Stage Down-conversion Architecture

In this architecture, Ka band RF input signal is down-converted to S-band fixed frequency IF signal (IF1) using a variable Local Oscillator (LO) signal. The IF1 is down-converted to the final IF frequency IF2 at VHF band. The simplified block diagram of this architecture is shown in Fig. 5.

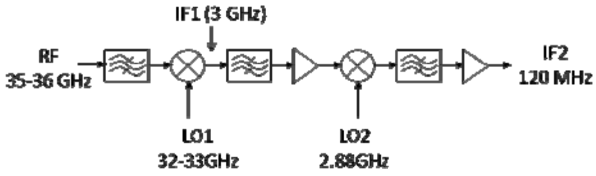

Fig. 5 Architecture of two stage down converter

Spurious analysis is carried out for both the mixing stage to finalize the LO and IF frequencies. The spurious analysis is shown in Fig. 6. In first mixing stage, there is no RF frequency inside the RF bandwidth that can generate IF1 signal as a result of inter-modulation. But there are few out-of band RF frequencies, which can generate inter-modulation products of 4th, 6th and 8th order. These frequencies should be considered as these are nearby to the RF band. Therefore, suitable RF band pass filter should be put ahead of the mixer so that the filter roll off will provide additional rejection in addition to the mixer inter modulation rejection.

LO Frequency Range:	32	to	33	GHz
IF Frequency Range:	3	to	3	GHz
Desired M (RF Harmonic) Value:	1			
Desired N (LO Harmonic) Value:	-1			
Spurious Response Search Range:	33	to	38	GHz
Full RF Frequency Range:	35	to	36	GHz

I. M (RF Harmonic) > 0, N (LO Harmonic) < 0

N ↓ / M →	1			2			3			4		
-1	35.00	-	36.00	17.50	-	18.00	11.67	-	12.00	8.75	-	9.00
-2	67.00	-	69.00	33.50	-	34.50	22.33	-	23.00	16.75	-	17.25
-3	99.00	-	102.00	49.50	-	51.00	33.00	-	34.00	24.75	-	25.50
-4	131.00	-	135.00	65.50	-	67.50	43.67	-	45.00	32.75	-	33.75

II. M (RF Harmonic) < 0, N (LO Harmonic) > 0

N ↓ / M →	-1			-2			-3			-4		
1	29.00	-	30.00	14.50	-	15.00	9.67	-	10.00	7.25	-	7.50
2	61.00	-	63.00	30.50	-	31.50	20.33	-	21.00	15.25	-	15.75
3	93.00	-	96.00	46.50	-	48.00	31.00	-	32.00	23.25	-	24.00
4	125.00	-	129.00	62.50	-	64.50	41.67	-	43.00	31.25	-	32.25

Desired RF Response	User Input Cells
Spurious Responses (Inside Search Range)	Spurious Responses (Inside RF Band)

Fig. 6 Spurious analysis of First mixing stage of two stage architecture

In the second mixing stage also, the nearest frequency to the mixer input frequency that can generate IF2 as 4th order inter-modulation products, is at 2.94 GHz. There are also few input frequencies that generate 4th, 6th, 7th and 8th order inter modulation products along with the image frequency. All of these input frequencies including the nearest one can be easily suppressed by using a suitable band pass filter ahead of the second mixer in addition to the inter modulation rejection of the mixer. Spurious analysis of second mixing stage is shown in Fig. 7.

LO Frequency Range:	2.88	to	2.88	GHz
IF Frequency Range:	0.12	to	0.12	GHz
Desired M (RF Harmonic) Value:	1			
Desired N (LO Harmonic) Value:	-1			
Spurious Response Search Range:	2	to	4	GHz
Full RF Frequency Range:	3	to	3	GHz

I. M (RF Harmonic) > 0, N (LO Harmonic) < 0

N ↓ / M →	1			2			3			4		
-1	3.00	-	3.00	1.50	-	1.50	1.00	-	1.00	0.75	-	0.75
-2	5.88	-	5.88	2.94	-	2.94	1.96	-	1.96	1.47	-	1.47
-3	8.76	-	8.76	4.38	-	4.38	2.92	-	2.92	2.19	-	2.19
-4	11.64	-	11.64	5.82	-	5.82	3.88	-	3.88	2.91	-	2.91

II. M (RF Harmonic) < 0, N (LO Harmonic) > 0

N ↓ / M →	-1			-2			-3			-4		
1	2.76	-	2.76	1.38	-	1.38	0.92	-	0.92	0.69	-	0.69
2	5.64	-	5.64	2.82	-	2.82	1.88	-	1.88	1.41	-	1.41
3	8.52	-	8.52	4.26	-	4.26	2.84	-	2.84	2.13	-	2.13
4	11.40	-	11.40	5.70	-	5.70	3.80	-	3.80	2.85	-	2.85

Desired RF Response	User Input Cells
Spurious Responses (Inside	Spurious Responses (Inside RF

Fig. 7 Spurious analysis of Second mixing stage

This architecture has better SWaP factor, less implementation cost and better reliability than the previous architecture. But it is to be noted that the LO1 is at Ka band with 1 GHz RF bandwidth. Generation of LO at Ka band is costly and less reliable. Moreover, the nearest image frequency will be at 30 GHz, which has to be filtered prior to the first mixer. Filtering of the second image frequency is also very critical, but possible using of the ceramic filters.

III. TWO STAGE RECEIVER ARCHITECTURE WITH SUB-HARMONIC MIXING

With the advancement of the mixer related technologies, Sub-Harmonic Mixers [2] (SHM) attained popularity over last few years for application in Ka band and above. Sub-harmonic mixers offer an alternative to fundamental mixers in that the LO frequency is at some integer fraction of the fundamental LO frequency, where $\omega_{IF}=(\omega_{RF} - n*\omega_{LO/n})$. The first down converting fundamental mixer can be replaced by a sub harmonic mixer to reduce the complexity in generation of Ka Band LO. The filtering requirements of the LO chain is also reduced. This advantage directly translates to lower costs while maintaining the electrical performance of the system. The SHMs are available with the IF support up to 4GHz.

We have seen in the previous section that two stage down conversion architecture is better than the three stage architecture. The main drawback of the two stage architecture i.e. generation of Ka band LO can be reduced by replacing the first fundamental mixer with a SHM. This requires a Ku band LO instead of the Ka band LO.

Therefore, we have chosen a two stage down conversion architecture with sub-harmonic mixing for the first stage. The block diagram of this architecture is shown in Fig. 8.

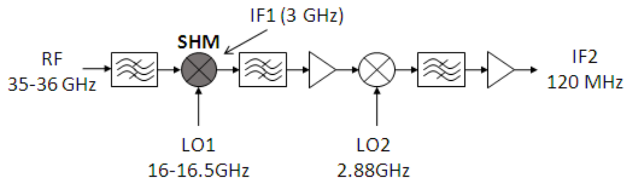

Fig. 8 Architecture of two stage down converter with sub-harmonic mixing

The second down conversion stage in this architecture is identical to the previous architecture. The spurious analysis for the first mixer is almost similar to that of a fundamental mixer except the fact that even order inter-modulation products are suppressed here. The SHM must have excellent 2*LO to RF isolation so that the requirements of filters are minimized.

IV. Architecture and Design

In this paper, we propose architecture of a Ka band RF front end [3] that can be used in a Ka band monopulse tracking Radar receiver. The architecture is based on two stage down conversion with a sub-harmonic mixing as discussed in the previous section. First down conversion here is part of the proposed RF Front end to minimize the insertion loss at Ka band. And the second down conversion is a part of IF receiver. The block diagram of the proposed RF Front end is shown in Fig. 9.

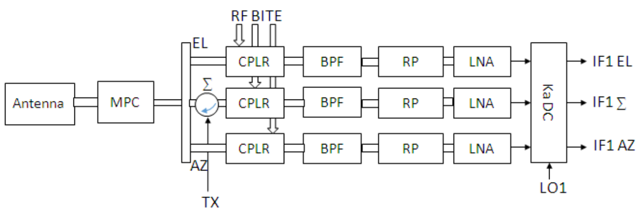

Fig. 3 Block diagram of Ka band RF Front end.

Most of the components of the RF Front End are waveguide components with very low insertion losses in order to keep the Noise Figure of the complete chain within required limit. The target echo signal is received by Antenna, which is a reflector based Antenna with a feed horn. The received signal is passed through a monopulse comparator in order to generate sum and difference signals. In the sum channel, a duplexer is placed that enables use of the same antenna for both transmission and reception. The duplexer may be a 4 port circulator capable of handling the required transmit power. The 4th port should be terminated by an appropriate load. Typical achievable Tx-Rx isolation of the duplexer is around 20 dB.

The couplers in the following stage are used for simulated target injection into the main channel at RF level (i.e. at Ka band). The health of the complete receive chain including IF stage can be checked using the injected RF BITE. The coupling value should be at least 50 dB so that the noise floor present in the RF BITE path does not dominate over the noise floor established in the main channel. The Band Pass filters are used for out of band interference rejection as well as image frequency rejection. The image frequencies corresponding to the first mixing stage must be suppressed prior to the mixer present at the KaDC (Ka band Down Converter) module. In the present case, the nearest image frequency is at 33 GHz which must be suppressed at least by 60 dB in order to achieve 60 dB image rejection. Waveguide band pass filters are available with this type of rejection requirement.

The receiver protector is required to protect the receive chain especially the LNA against the transmit leakage. The worst case transmit leakage appears at the receive chain as a result of poor Antenna return loss as compared to the direct leakage from the Tx port to Rx port of the duplexer. For example, if the worst case Antenna return loss is 10 dB and the Tx/Rx isolation of the duplexer is 20 dB, the transmit leakage that appears in the receive chain is approximately 10 dB down the transmit power. Based on the transmit power level, the receiver protector can be a Pre-T/R tube or a T/R tube or a solid state limiter or combination of them. The other parameters that need to be considered are spike leakage, flat leakage and recovery time. The spike leakage must be less than the LNA input damage level.

Selection of the LNA is very important as it determines the Noise Figure of the overall receive chain, thereby directly controlling the receiver sensitivity. The gain of the LNA should be high enough to keep the Noise figure contribution due to the following receive chain is very less. And the Noise figure of the LNA should be low enough to keep the sensitivity within specification.

The Ka DC block is responsible for the first down conversion employing sub-harmonic mixing and filtering of the IF1 signal.

V. Conclusion

The proposed architecture in this paper provides is a generic low noise Ka band RF Front End employing a sub-harmonic mixing stage, which can be used as the RF front end of a monopulse tracking radar. Due to the sub harmonic mixing, the generation of LO becomes less complex, less costly and more reliable. Proper frequency planning ensures spurious rejection to the desired level.

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Rajasekhar Adigopula was born in 20 Aug 1978. He received B.tech degree in Electronics and Communication Engineering from S V Hindu College of Engineering, Machilipatnam, Andhra Pradesh in 1999. He joined Bharat Electronics Ltd, Bangalore in 1999 Since then he had involved in various development programs of Air defence radars and testing of sub systems and systems of the radar. His primary areas of interest covers Radar system Designing, system Integration, Testing of various RF and Digital sub systems etc.