Non-Linear Junction Detector

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Punit has helped us in the selection of power amplifier and low noise amplifier. He designed the circuit layout for the power amplifier and tested its response. He has also helped us in soldering and testing of other components.

Abhay helped us in making the shielding boxes using the aluminium sheets. He made the layout for the packaging of the device. He also tried new ideas for antennas.

Manoj designed the high order low pass filter. He did the simulation required to come up with the filter design. He fabricated the filter and tested its response. He also designed a box to shield the filter.

Ajay has assited us in working out the details for using the RF microcontroller.

Salil has given us valuable suggestions in all aspects and resolved many of our doubts. He has helped us in the selections of the components.

We are also thankful to RAs in Antenna Lab, especially Rinkee, for their help.

Abstract

A non-linear junction detector, or an NLJD is a counter-surveillance tool commonly used for detecting hidden transmitters or other electronic items. The device illuminates a small region of space with high-frequency RF energy. Any "non linear junction" in the vicinity, for example, and particularly, the p-n junction will receive this energy, and because of the non-linear nature of the junction, it will re-emit harmonics of the illumination frequency. The detector detects these harmonic frequencies. Because the basis of almost all semiconductor electronics is the p-n junction, an NLJD is correspondingly capable of detecting almost any un-shielded electronic device containing semiconductors, whether the electronics are on or off. radiations.

Contents

1 Introduction

NLJD got a reputation as perfect means of counter-espionage, as embassies and other diplomatic posts are known to be most popular targets for eavesdropping equipment. Some specific models of NLJD are used by the police in search for weapons during events involving great masses of people. These detectors are used for providing location secure from covert listening devices in different organizations.

Our motivation for the project however arose as it was floated as a project under NCETIS. In the naxalite affected regions of the country, the naxals regularly plant bombs under roads which are remote controlled. Detecting these is crucial for the CRPF jawaans. These bombs are a major cause of casualties to our security forces. NLJD is the most effective tool for them in order to counter this threat.

Currently the NLJDs used are imported from Germany and other places. They prove to be very expensive (around Rs. 12lakh per piece). Moreover the spare parts aren't easily available in the country and the foreign companies make a killing in supplying them. Thus there is a great need for indigenization of this device.

Indigenization would also allow to have the NLJDs customized to their requirements. In one meeting with some officers from the CRPF which Prof. Karandikar had arranged for us in our second year, we learned of many requirements from their side. The following were some of the practical specifications which they wanted the product to have -

- Atleast 2ft detection range in wet soil
- Battery life: 5-6hrs
- Battery should be easily available in market
- Lightweight overall equipment

The project objective was to improve upon the Non Linear Junction Detector made in EDL1 and attempt to take it to a prototype level from the proof-of-concept stage.

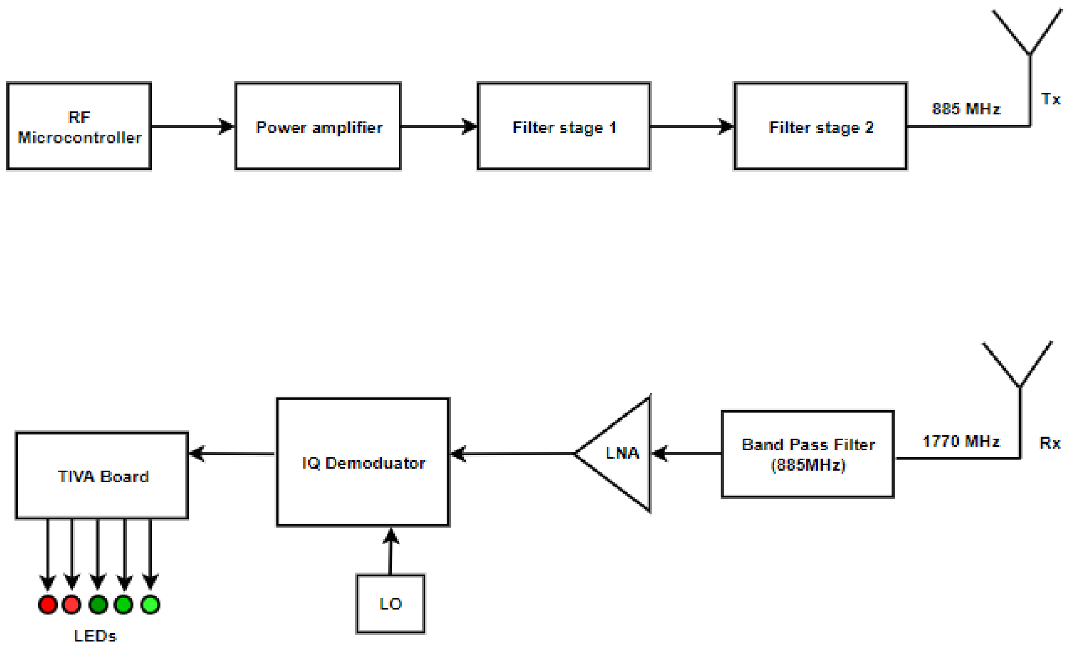

Figure 1: System Block Diagram

The technique used to demonstrate the proof of concept and hence build a prototype of NLJD is presented in above block diagram. The details of each of the subblocks/components are provided in later sections.

2 Antenna Module

We have created an enclosure for the antennas. For this a Solidworks design was built which contained compartments for the three antennas, and some space behind them in order to put metal foil or RF absorbing material so that reflections from the backside can be reduced. Then there is a pipe attached to this antenna head which acts as the handle from where to hold it. The wires from the antennas are also carried within it.

We obtained 55dB isolation between the transmission and receiver antennas.

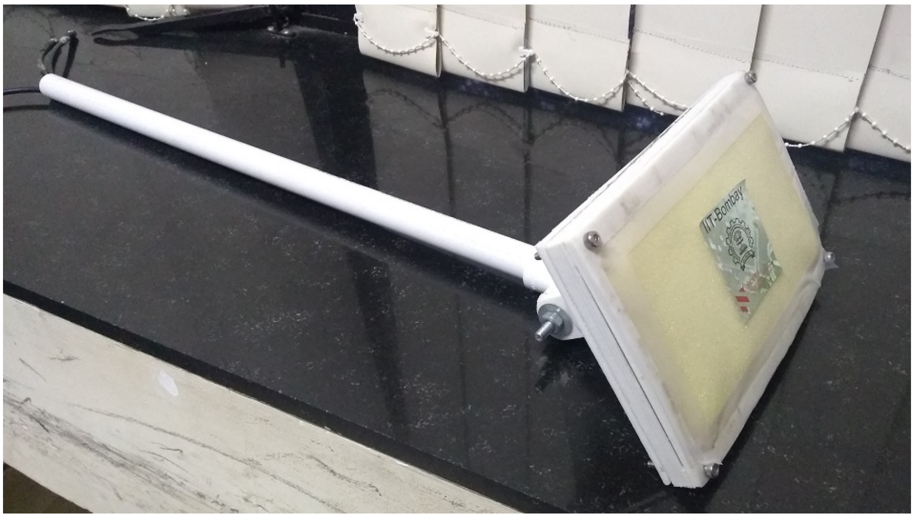

Figure 2: Final antenna head

3 Shielding

3.1 Aluminium cases

For the purpose of shielding and proper placing of the components, we first ourselves built boxes using aluminium sheets. The sheets were cut into two strips and then these were bent in order to form two C-shaped parts which when put together form the entire shielded cover. We did all this work in the NCPRE lab which lies adjacent to the Tinkerer's Lab.

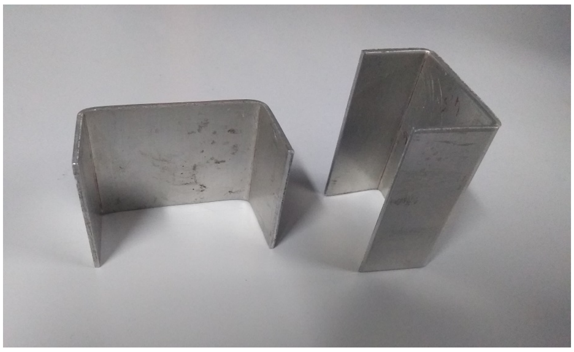

Figure 3: The C-shaped parts

Figure 4: Aluminium boxes made by us

And then we fixed our components on another aluminium sheet. Semi rigid cables were used and this eliminated many long SMA cables used uptill now and simplified further work.

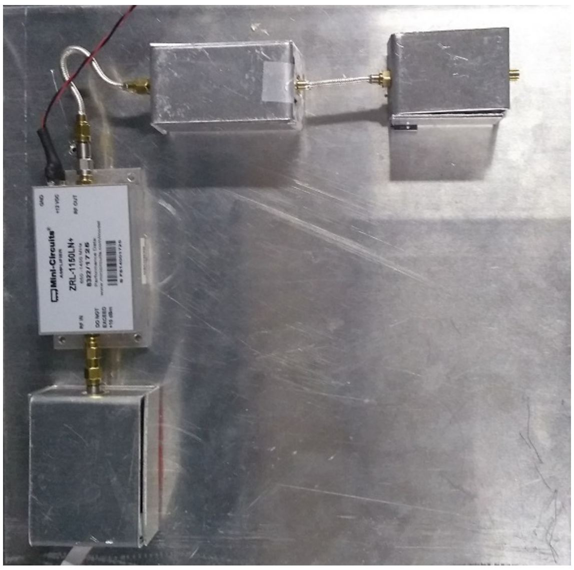

Figure 5: Tx chain components properly placed and connected with semi-rigid cables

3.2 Milled aluminium boxes and EMI gaskets

Later proper aluminium boxes were designed using Solidworks and manufactured from outside. So now our components will be placed inside these boxes and this should bring down the radiations. We have also bought EMI gaskets for this purpose.

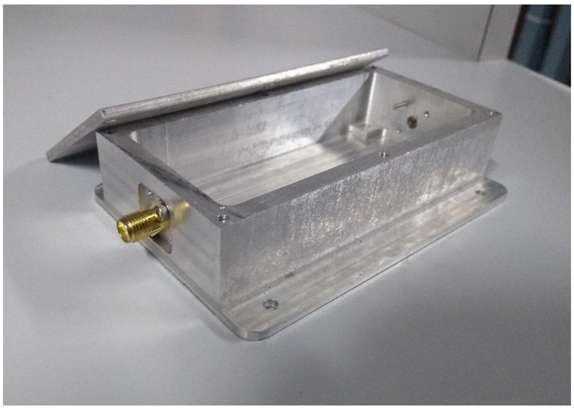

Figure 6: Manufactured aluminium boxes

4 Filters

4.1 Cascading Effect

Cascading filters in series may be used to enhance stopband rejection and steepness in the transition band. The technique can also be used to combine high pass and low pass filters to create a bandpass response. But conventional filters are fully reflective in the stopband, and the reflected signal creates standing waves in the signal path between filter stages. Suppose two filters are in cascade, then the signal that is stopped by the second filter is reflected back, but the reflected signal again sees a filter (the first filter) which again reflects the signal towards second filters, this ultimately results into the formation of standing wave. Some of the problems created by this are:

- Due to the formation of the standing wave, nearly half power is passed through both the filters. This results in only a 3 dB increase in the stopband rejection by cascading the filter.
- This also introduces problems in the passband such as ripple and phase instability, which distort the desired signal and degrade system performance.
- The power amplifier we are using also has a built-in filter in its circuit. Due to this, our filter, ahead of the power amplifier, is rendered useless.

There are some ways to evade this issue:

- **3dB attenuator**: By using an attenuator in between the filter stages, one could restrict the formation of standing waves. A 3dB attenuator decays the signal strength that is moving back and forth between the two filters and thus, the stopband rejection is improved by around 20dB. But this also increases the overall insertion loss by 3 dB. So, we are using the attenuator in between that power amplifier and the filter so that the power loss due to attenuator could be accounted for by the power amplifier. Increase in the insertion loss is however a case against using high value attenuators.
- **Reflectionless Filters**: Reflectionless filters, as the name suggests, try to minimize the reflected power of the signal that is rejected by the filter. Their

aim is to make the S_{11} response to also be zero for the out of band signal. The rejected signal is passed through a resistor which absorbs the signal power. But the problem with these filters is that their stopband rejection is not high enough for our purpose. The details about the topology of these filters can be found in the paper *Reflectionless Filter Structutes* [https://arxiv.org/pdf/1407.7825.pdf].

- **Crystek LPF**: The low pass filter from crystek are 7^{th} order butterworth filter matched with 50Ω SMA output. Their out of band suppression varies from $35 - 40$dB, which is less than the out band suppression of our 6^{th} order chebyshev filter (nearly 55dB suppression). The advantage of these filters are that they are properly shielded, so they work nicely when connected in cascade. But when they are connected in cascade, they suffer huge insertion loss for the frequencies near the cutoff value. The $S(2,1)$ response of CLPFL-1600 (cutoff $=$ 1600 MHz) is given as below

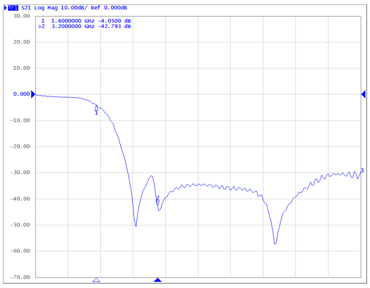

Figure 7: Response with only one filter

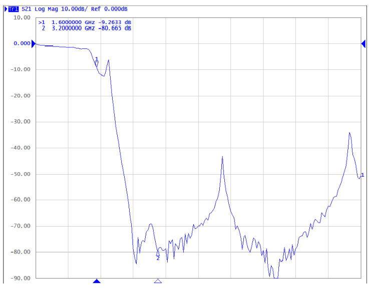

Figure 8: Response with two filters in cascade

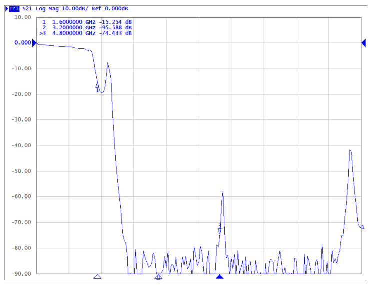

Figure 9: Response with three filters in cascade

We see that the cutoff frequency shifts when these filters are connected in cascade. Thus for lowpass filtering at 885MHz, we have ordered CLPFL-1200 (cutoff $=$ 1200 MHz), so that a small frequency shift does not create a problem.

4.2 Lumped Element filter

We have designed a 10^{th} order chebyshev filter, similar to the 6^{th} order chebyshev filter. The stopband rejection provided by this filter is much higher than the earlier filer. The major problem with Lumped Element filters is that it does not work in cascade. Shielding is also an issue for these filters. These filters emit significant power that can interfere with the received signal. This filter provided us with over 75dB stopband rejection at the harmonics.

5 Microstrip Filters

Microstrip filters use the properties of transmission line to filter out some of the frequencies. We have designed three types of microstrip filter. The microstrip filters give better suppression, especially for band pass filters, as compared to SAW filters or the lumped element filter. For low pass application, lumped element filters are better than microstrip ones. Where the SAW filters provide an outband suppression of nearly 20dB, Microstrip filters provide the suppression of nearly 40dB or more, while incurring nearly same insertion loss. But they are comparatively larger in size.

5.1 Stub Filter

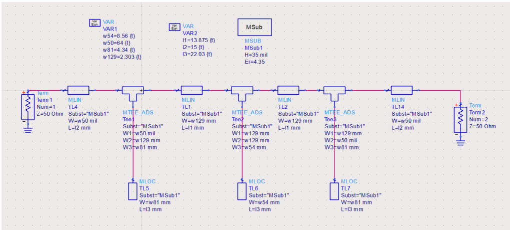

Figure 10: Schematic of Stub filter

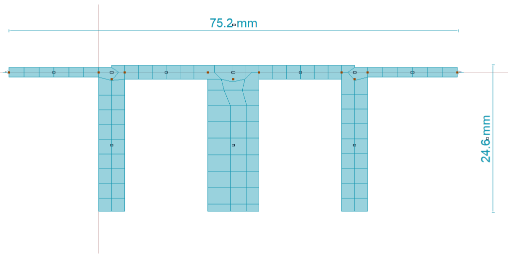

Figure 11: Layout of Stub filter

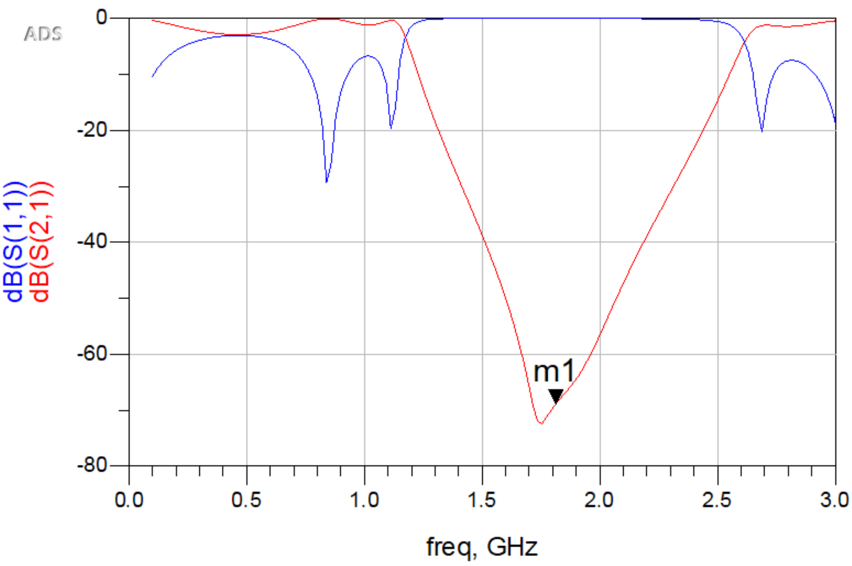

Figure 12: Result of EM Simulation in ADS

5.2 Parallel-Coupled Filter

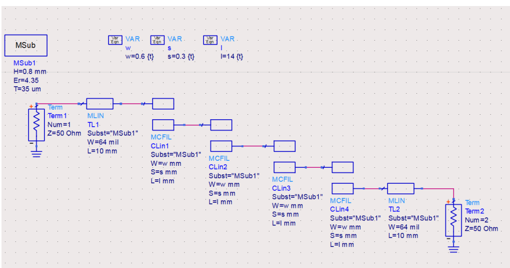

Figure 13: Schematic

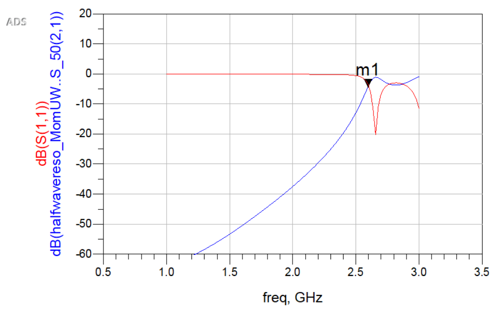

Figure 14: Result of EM Simulation

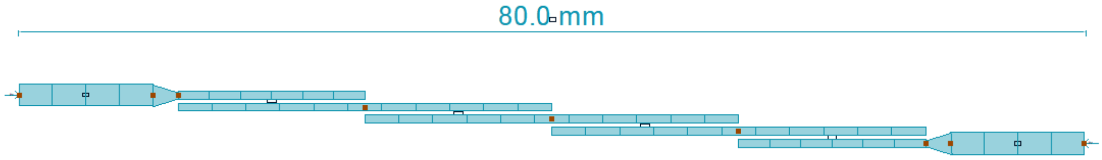

Figure 15: Layout of Parallel-Coupled filter

5.3 Hairpin Microstrip Filter

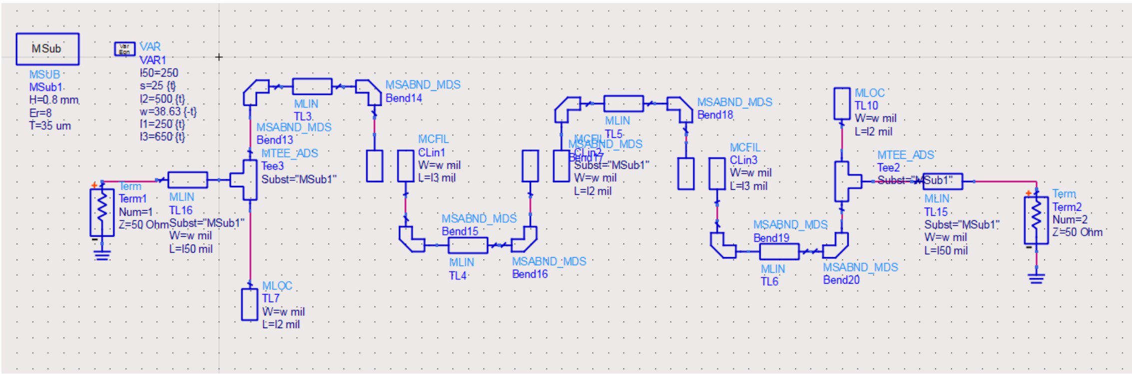

Figure 16: Schematic of Hairpin microstrip filter

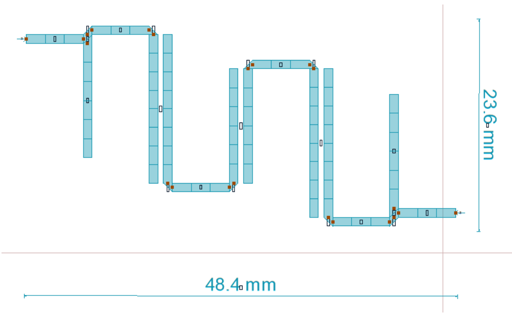

Figure 17: Layout

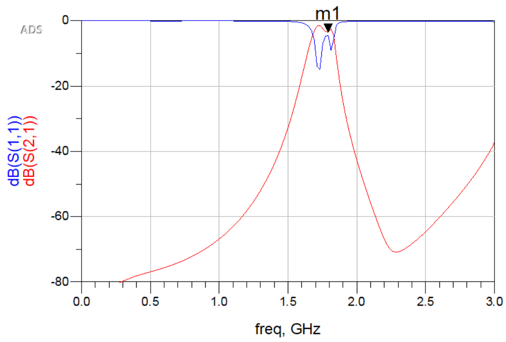

Figure 18: Result of EM Simulation

6 Signal Generation

6.1 Using PLL

The MAX2870 board developed in Communications Lab was programmed to generate 885Mhz signal. The power level was set to be the maximum supported by the board. The power levels generated we as follows:

- 1st harmonic : -4 dBm
- 2nd harmonic : -2.7 dBm
- 3rd harmonic : -20 dBm

6.2 Using RF micro-controller

We are now using RF micro-controller (AX8052F143) instead of the signal source. It generates carrier pulses at 885MHz at an output of 13dBm. The power levels observed are better than those obtained by the PLL and are as follows:

- 1st harmonic : 13.2 dBm
- 2nd harmonic : -40 dBm
- 3rd harmonic : -25 dBm

Figure 19: The RF microcontroller - AX8052F143

Harmonic Predistortion: The RF microcontroller which we are using has an option of harmonic pre distortion. The transmit predistortion circuit applies the following function to the output:

$$f(x) = \alpha_4 x^4 + \alpha_3 x^3 + \alpha_2 x^2 + \alpha_1 x^1 + \alpha_0$$

α_i's are programmed using various registers to apply suitable predistortion.

We tried using this method to predistort the generated RF signal and drive the power amplifier, but we went not able to observe any predistortion effect as stated in the datasheet. So we decided to drop this method.

7 Power Amplifiers

7.1 MMZ09332BT1

We decided to switch to a better power amplifier this time i.e. one with higher peak output power as well as higher IIP3. The PCB for it was designed as given in the datasheet. However we couldn't obtain the specs mentioned in the datasheet. It claimed a P1dB of 33dbm but we could only go upto around 23dBm. This could be due to improper impedance matching at some place.

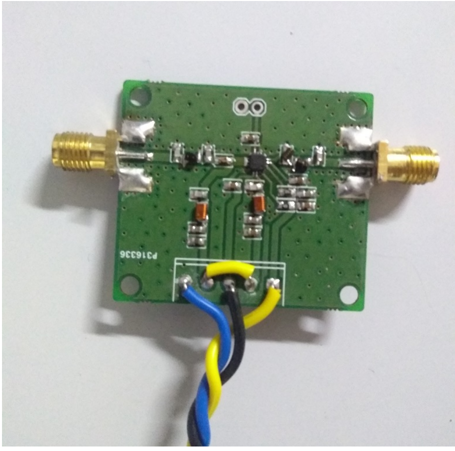

Figure 20: PCB for MMZ09332BT1

So we tried after removing a filter placed at the output of the IC as it might not have been properly matched. But then a lot of these ICs went bust when they were used continuously for some time.

7.2 ZRL-1150LN

We got another amplifier since many of the MMZ09332BT1 ICs had got damaged. ZRL-1150LN provides us a peak output of 24dBm but an advantage of having this was that it comes a properly shielding box. So currently we are using power amplifier.

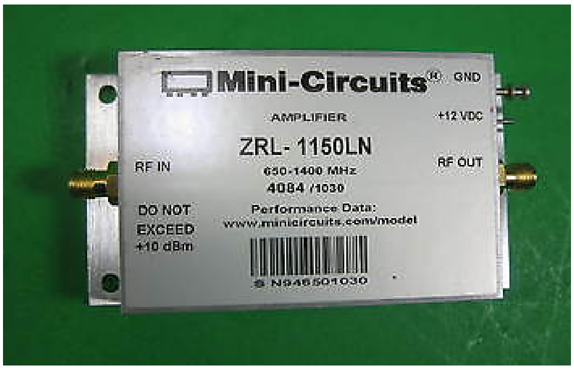

Figure 21: ZRL-1150LN

7.3 2nd Harmonic Shorts

One of the suggested ideas for removing the harmonic content generated by the power amplifier was to provide a low impedance path (a short) for the harmonic frequencies after the PA. The intention behind this was that instead of the standing wave forming between the filters, the harmonics can now take this alternate path and therefore their amount in our main signal path is reduced. Moreover if it works properly, it can be used to get cascading effect in filters as well. This approach also however failed to give desired results. We only got a 3dB reduction in the harmonic level most likely due to splitting o the harmonics equally between the low impedance path which we provided and the main signal path. We do not know why its happening as such.

8 LNAs

8.1 SGL0622Z

Earlier we were trying to use this LNA but the circuit was oscillating. We designed new PCB board with vias all over the board so that the feedback loop which might lead to oscillations is eliminated as now the surface waves wont be able to propagate over the PCB. This also however did not work. Surprisingly the circuit when built on a 1.6mm thick substrate (we were using 0.8mm thick substrate) did not give rise to any oscillations and also provided a very high gain of 26 to 28dB as mentioned in its specs.

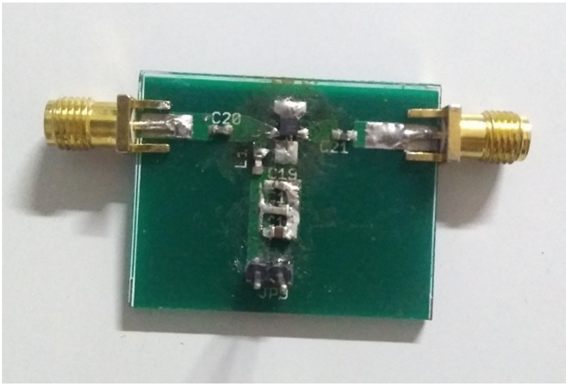

Figure 22: SGL0622Z on 1.6mm thickness FR4 substrate

Properly shielding it was however an issue and we decided to get a shielded LNA for the purpose.

8.2 ZX60-2534MA+

ZX60-2534MA+ is a general purpose amplifier which provides us a gain of over 40dB with a noise figure of 2.6dB only. This LNA is currently being used and proovides satisfactory performance.

Figure 23: ZX60-2534MA+

9 Power source

We have now removed the multiple power sources used until now for powering different components like the mixer, LNA, power amplifier and TIVA board. All of this now comes from a single board made using LM317 ICs which requires a single

12V supply. We intended to provide this as well from a battery thus eliminating laboratory power sources completely but using a lead acid battery substantially increased the overall noise in the system to the extent that it could not be used to detect non-linear junctions. We need to look further into the cause for this and see if other battery types are more suitable.

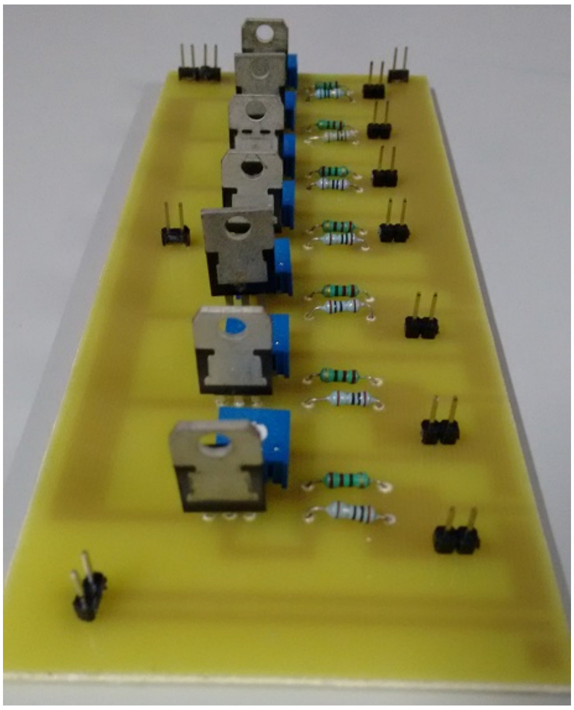

Figure 24: The board which provides various output voltages for the components

10 Baseband Signal Processing

The TIVA board (TM4C1294) is used to do the baseband processing. Baseband output from the mixer is sampled by this board at 130kHz. We then carry out FFT using 128 samples, average out the result over 10 cycles and then look at the amplitude at the desired frequency (60kHz). If this crosses a threshold, we say that a non-linear junction is present else not. The threshold is set in the setup loop of the program wherein upon looking at the default peak amplitude level of the baseband signal. This is useful in different environments as the ambient noise levels need not be same everywhere. The presence or absence of the junction is then indicated using LEDs controlled by the TIVA board itself.

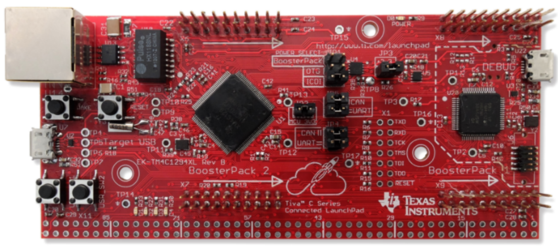

Figure 25: TM4C1294 TIVA board

11 Conclusions and Future Work

Our final transmission and receiver setup looks like this:

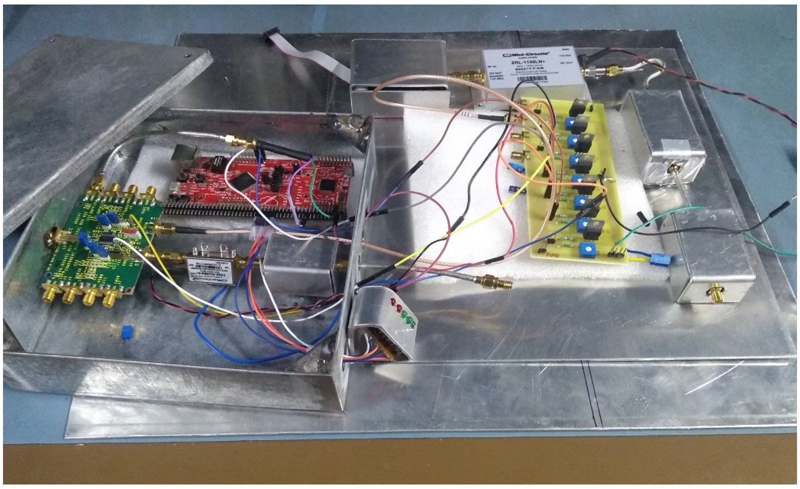

Figure 26: Transmission and receiver chains

- A laptop is also required as of now to power the RF micro-controller primarily because we were unaware as to which pins on the soldered board are used to power it. Also the laptop is required to operate the Vector Signal Generator which we are using to generate the LO signal for the AD8347 mixer. Thus we need to make a **PLL circuit for generating LO signal**. This is not a challenging part as we aren't concerned with the presence of harmonics in the LO signal.

- Upon using the new Keysight MXG Analog Signal Generator to generate the 885MHz transmit frequency at 27dBm output power, we were able to obtain the best results i.e. no false positives and minimum noise in the system. Thus it can suffice to say that having a proper **high power signal source** is very important for the functioning of the device and therefore the role of the power amplifier is crucial.

- The setup can detect signal with strengths as low as as -130dBm. We can say so by considering that the LNA gives us a gain of 40dB followed by a further gain of 50 to 55dB by the mixer. The output of this mixer when seen of the signal analyser is around -40dBm while the noise floor stays varies from -50 to -60dBm. Thus a simple **amplifier at the end of the mixer** can potentially increase the sensitivity by 10dB to -140dBm.

- Regarding antennas, it would be beneficial to have **circularly polarized antennas** because currently the detection is extremely sensitive to the orientation of the device under test.

- Using a lead acid battery source currently causes a huge increase in the noise floor (around 15dB). Possible reason for this a suggested by sir is that the battery which we used couldn't source the current required for a long time. It discharged very quickly. Ideally a battery should lead to lower noise levels as the output is a very stable DC output unlike the lab power source which has some amount of ripple in it.

- We have been able to get rid of most laboratory equipments this time - the spectrum analyser, signal source and multiple power sources. Also the entire device is now much more compact.