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# Development of C-Band RF Front-end of Precision Coherent Mono-pulse C-Band Radar

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**ABSTRACT**

A compact, robust and high performance front-end of a radar receiver is designed and demonstrated in this paper. The important parameters like noise figure, sensitivity, selectivity, dynamic range and tracking range are superior to that of the existing systems and facilitate online monitoring of the above important parameters. The gain and phase matching facility are incorporated. The local oscillator is integrated within the module which in turn reduces the losses as compare with the existing local oscillator, placed in the instrumentation cabin. The frequency, amplitude, delay between skin and transponder frequency can be controlled remotely by computer program. Therefore, the mixed mode operation (skin and transponder) of radar receiver is possible. Moreover, the SPDT switch is integrated in the same module for RF simulation to facilitate the three channel mono-pulse receiver calibration, receiver health monitoring and range calibration of precision coherent mono-pulse C-band radar. The components used are monolithic microwave integrated circuit based technologies with superior specifications, makes the total module miniaturized and reduced the hardware complications. The total power consumption is much less and improves the overall performance than the existing front-end.

**Keywords:** Sensitivity, dynamic range, noise figure, RF simulation, phase noise, phase matching, gain matching, PCMC radar

## 1. INTRODUCTION

The radar receiver consists of three parts, the receiver front-end operating at radio frequency, IF processing unit which works with the IF frequency and DSP unit which works with the baseband signal derived after IF processing. Receiver front-end is an important part of the radar system. The front-end is based on the mono-pulse techniques which are invariably used in all modern tracking radar for angle tracking. The RF front-end receiver or super-heterodyne receiver includes low noise amplifier and mixer. The first stage of RF front-end is low noise amplifier[1-3]. The total noise figure is mostly depending on the noise figure of LNA. The dynamic range can also be enhanced by the LNA. Therefore proper choice of LNA will give significantly improved performance of the radar. The output of LNA can be controlled by the strength of signal (AGC) so that the dynamic range of the receiver increases[2].The radar is desired to perform normally at the closest range and at the same time providing maximum detection range. All this factors leads to the requirement of very high dynamic range mono-pulse angle tracking receiver to extract mono-pulse error of weak target echo in the presence of strong interference[4,5]. The phase and gain matching between the three channels are properly controlled to extract mono-pulse error correctly and obtain more accurate tracking by the radar. In this paper the new design configuration and feature of the front-end of the receiver is presented. The entire active and passive components used in the receiver front-end are realized in monolithic microwave integrated circuit (MMIC) chip-based technique which in turn minimizes the power consumption from 50 W to 28 W. The detail design parameters of the individual microwave components which are used in the new front-end are chosen such a way to get maximum improved target tracking range is discussed in the paper. The target tracking range capability of precision coherent mono-pulse C-band (PCMC) radar both skin (improved from 90 km to 120 km) and transponder (improved from 1600 km to 2200 km) mode are enhanced appreciably in the newly designed front-end. The related parameters like sensitivity, dynamic range, noise figure and phase noise are improved compared to the existing system which leads to the improvement of the target tracking range capability.

## 2. THEORY

In the super-heterodyne receiver, the signal voltage is combined with the local oscillator voltage and normally converted into a signal of a lower fixed frequency[1-3].

Noise figure is a measure of noise produced by a practical receiver compared to the noise of an ideal receiver. The noise figure ($F_n$) of a linear network having available gain $G$, noise bandwidth ($B_n$), with $N_{in}$, and $N_{out}$ are input and output noise power defined as[3,6,7].

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$$F_n = \frac{N_{out}}{T_o B_n G} \text{ or } \frac{S_{in}/N_{in}}{S_{out}/N_{out}} \quad (1)$$

noise figure of networks in cascade is

$$F_{sys} = F_1 + \frac{F_{2-1}}{G_1} + \frac{F_{3-1}}{G_1 G_2} + ... + \frac{F_{n-1}}{G_1 G_2 ... G_{N-1}} \quad (2)$$

and $Fsys = \frac{ENR}{Y-1}$ (3)

excess noise ratio (ENR) = $ENR(dB) = 10\log(\frac{T_h - T_c}{T_o})$ (4)

$T_h$= temperature of the hot load and $T_c$= temperature of cold load. $T_0$ = standard temperature of 290 K

Y factor ($Y$) = $\frac{N_2}{N_1}$

where $N_1$ = noise power when noise source is OFF and $N_2$= noise power when noise source is ON.

Dynamic range[7] (DR) = P1dB(in) $-N_i$ (5)

Noise power at receiver input ($N_i$) = $kT_oBF_n$ (6)

*P1* (dB) = 1dB compression point

*B* = bandwidth of receiver

In this study the trade off between bandwidth, gain, noise figure, dynamic range and frequency of components like amplifier and mixer are well optimize to get best result out of it.

## 3. SYSTEM DESIGN AND DESCRIPTION

Figure 1 shows the block diagram of the newly designed C-band RF front-end. This design has a facility to feed the RF signal with proper delay to get the simulated target. This target can be used for range calibration of radar and the strength of the return signal gives the health status of the receiver. The RF signals from stable master oscillator (STAMO) fed to dual isolator so that it protects the STAMO from reverse power. The output of the isolator 1 is fed to the SPDT switch. The SPDT switch converts the CW signal to pulse modulated signal. The modulation can be controlled by the radar sync pulse fed to control port of the SPDT switch. The SPDT switch having one RF-In port and two RF-Out ports. The author used port2 and port1 is made match termination. The output of the switch is made either pulsed modulated or CW depend on the requirements by the control signal fed to control port of the switch. The output of the switch is fed to dual isolator2 to protect the switch. Further it is fed to three-way power divider, so that the input power is getting divided into three, as the current design of front-end is a three channel mono-pulse. Therefore the three equally dividing power is fed to the three channels. Three channels consist of direction couplers followed by low noise amplifiers, dual isolators, variable attenuators and finally image rejection mixer. While simulation the couple port (20 dB) of directional coupler is used and for normal operation direct port is used. The detailed proposed newly design, specifications and some important measured parameters of each components used are described below.

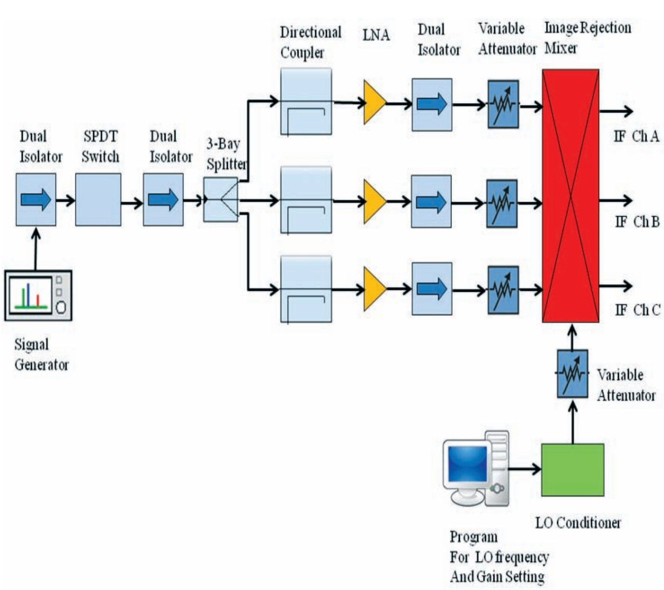


**Figure 1. Block diagram of the newly designed RF front-end.**

Figure 2 represents the pictorial view of the newly design RF front-end. The components used are MMIC-based technology. The components layouts are reflected in the Fig. 2. The different monitoring points viz. LO-output, noise figure, phase and gain points, LO-phase noise, channel IF-outputs and total power consumption are incorporated. The simulated input signal from the radar and the noise source/RF-input fed to the input of directional coupler for noise figure monitoring are also shown.

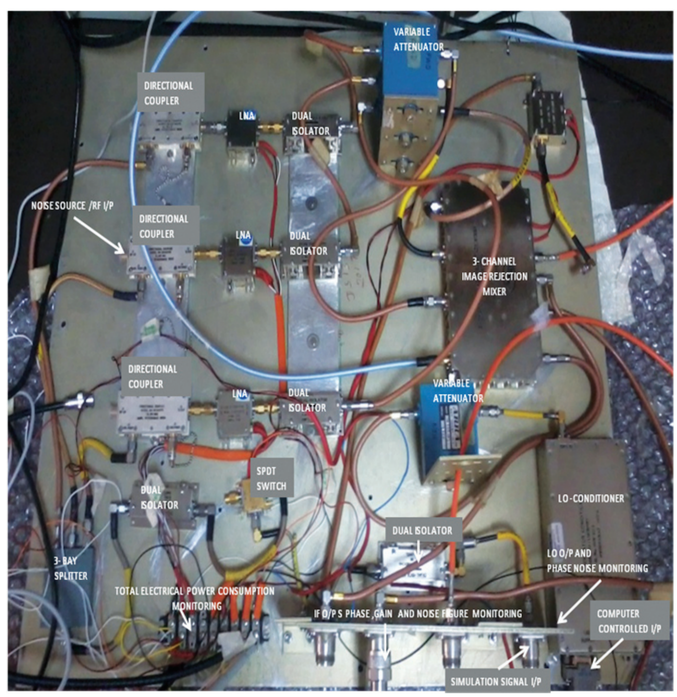


**Figure 2. Pictorial view of RF front-end module.**

### 3.1 PDT Switch

The proposed design of a C-band SPDT switch module is designed to work in C-band frequency. This module works with single control along with DC supply voltages of +5 V and -15 V, respectively. This switch module was realized on 5 mil RT5880 (RT Duroid) substrate using 0.5 µm pHEMT technology. This module was provided internally with decoupling capacitors (DC) in order to isolate the switch with external supply voltages. This SPDT switch has on-chip TTL driver. The achieved results of the SPDT are :

| *Parameters* | *Achieved Results* |
|---|---|
| Frequency | : C-band |
| Insertion loss | : 1.3 dB |
| Speed | : < 80 ns |

### 3.2 Directional Coupler

The proposed design of a broadband DC covering 2 GHz to 18 GHz. Directional coupler is designed with stripline configuration. This shows the stable performance across a broad frequency band.

Directivity (dB) = Isolation (dB) Coupling (dB)

The achieved results are :

| *Parameters* | *Achieved Result* |
|---|---|
| Frequency | : C-Band |
| Coupling | : 20 dB ± 0.85 dB |
| Insertion loss | : < 1 dB |
| Isolation | : > 32 dB |

### 3.3 Isolator

The Isolators are used to protect the device from reflection power at different load conditions. Therefore isolators are used at different positions in the RF front-end. The isolators are integrated at the output of STAMO, SPDT switch and three LNAs. The achieved results of the proposed design of isolator are :

| *Parameters* | *Achieved Results* |
|---|---|
| Frequency range | : C-band |
| Insertion loss | : 0.8 dB (dual) 0.5 dB (single) |
| Isolation | : 35 dB (dual) 20 dB (single) |

### 3.4 Low Noise Amplifier

The low noise amplifier is a vital part and first stage of the RF front-end[8-11]. It decides the overall noise figure of the RF front-end. Therefore the design concept of LNA is very crucial and different design methods are adopted[13-16]. This proposed newly designed of low noise amplifier is a single stage design which is developed using MMIC approach. The amplifier module was realized on 5 mil RT5880 (RT duroid) substrate to minimize the transmission losses. The +15 V DC is fed to NJM78M05 as a voltage regulator. The regulator output is connected to MAX881 (low noise voltage inverter device) to generate -0.3 V as Vg1 and another output connected to power MOSFET (ZXM62PO2E6) to generate 4 V as Vd and 2.5 V as Vg1. The Vd, Vg1 and Vg2 are connected to LNA chip AMT 2132011. This module is provided with on-chip gain control facility at the output of AMT 2132011 to control the gain of LNA through voltage variable attenuator (VVAChipHMC712) with a single TTL control 0 V to 2.5 V. The Gain of LNA can be controlled by varying the control voltage ($V_c$) of the VVA from 0 V to 2.5 V in steps of 0.25 V. VVA produces minimum attenuation level at $V_c$ = 0 V (Gain 17 dB) and maximum attenuation level at $V_c$ = 2.5 V (Gain 3 dB). This feature is utilized for sensitive time control (STC) of radar front-end and enhances the dynamic range of the radar. The module was designed for 1.1 dB noise figure compared to the existing LNA of 1.9 dB[2,7,8], so that the receiver sensitivity can be improved significantly. It was designed for +9 dBm output P1dB (P1dB greater by 9 dB compared to the existing specification is 0 dBm), so as to ensure that the module can be operated well within the linear region[15]. This module features OIP3 (output 3rd intercept point) greater than 25 dBm. The achieved results are shown below.

| *Parameters* | *Achieved Results* |
|---|---|
| Frequency | : C-Band |
| Gain (min) | : 15 dB |
| Noise figure | : 1.2 dB |
| 1dB compression O/P | : 8 dBm |
| VSWR | : 1.8 : 1 |
| Attenuation control voltage | : 0-2.5 V |
| Power supply | : +15 V |
| Supply current | : 70 mA - 100 mA |

### 3.5 Local Oscillator Conditioner

The local oscillator conditioner is basically a phase locked loop oscillator followed by a digital attenuator, driver amplifier and power amplifier. Isolator is kept at the output of the power amplifier to protect from reflection power at different load conditions. The low-pass filter is used at final stage to eliminate the harmonics which are generated by the power-amplifier (PA)[2,7].

A PLL consists of a voltage-controlled oscillator (VCO)[17], reference oscillator, loop filter followed by a loop amplifier and phase detector. In this design we chose a VCO of frequency range of C-Band with tuning step size of 10 MHz and voltage tuning of 12 V. The VCO is initially tuned to a frequency close to the desired frequency. If the VCO frequency departs from the selected crystal reference frequency, the phase comparator produces an error voltage that is applied to loop filter & loop amplifier, bringing the VCO back to the reference frequency. The PLL, VCO, reference oscillator and phase comparator together comprise a frequency synthesizer. Selecting the external TTL commands (GUI) to change the frequency from C-band frequency  in steps of 10 MHz. The output can be adjusted by the 6 bit digital attenuator (out of 6 bits two bits are tired to 5 V) from 25 dBm to 17.5 dBm in steps of 0.5 dB by giving the suitable 4-bit controls to the HMC425LP3. The HMC425LP3 is a broadband 6-bit GaAs IC digital attenuator covering entire C-band frequency. Gali-39 and Gali-84 are used as a driver to the power amplifier with a gain of 27 dB. MAAM26100-B1 is a GaAs MMIC two stage high efficiency power amplifiers in a small ceramic package having an output power of 30 dBm. The above controls are generated by small FPGA-based digital board with

RS-232 serial port. A GUI-based program generates the suitable control and command to the digital board to the corresponding section. The unit is operated by +15 V supply. The achieved results are :

| *Parameters* | *Achieved result* |
|---|---|
| Frequency range | : C-band |
| Power output | : +25 dBm |
| Harmonic contain | : -20 dB down |
| Spurious | : -20 dB margin to the optimum |
| V.S.W.R | : 1.5 : 1 |
| Power supply | : +15 V |
| Phase noise | : -8 dBc/Hz |
| Attenuation | : 1 dB step |
| Attenuation controls | : 3BIT |
| Interface | : RS232 |

Table 1 illustrates the output power and phase noise of LO at different frequencies. The overall phase noise in the total frequency spectrum is far better than the existing front-end. The maximum phase noise is -90.7 dBc/Hz at 5.6 GHz which is appreciably high than the existing value of -70 dBc/Hz at 5.6 GHz. The output power 26.5 dBm at 5.4 GHz is appreciably high compared to the existing value of 16 dBm at 5.4 GHz.

**Table 1. Output power and phase noise of local oscillator at different frequencies**

| Frequency (GHz) | Output power (dBm) | Phase noise @10khz offset (Dbc/Hz) |
|---|---|---|
| 5.4 | 26.50 | -90.26 |
| 5.5 | 25.50 | -90.15 |
| 5.6 | 25.20 | -90.70 |
| 5.7 | 25.03 | -89.63 |
| 5.8 | 24.80 | -88.67 |
| 5.9 | 24.70 | -84.37 |

### 3.6 Mixer

The mixer is a key element in the super-heterodyne receiver. The mixer should have low conversion loss, introduce little addition noise of its own and minimize spurious response. The noise figure of a mixer is determined by its conversion loss and noise temperature ratio[1]. The noise temperature ratio of a mixer varies inversely with the IF frequency. The lower the conversion loss, the large is the noise temperature ratio[2].

An ideal mixer is one whose output is proportional to the product of the RF echo signal and the local oscillator (LO) signal. The $f_{RF} > f_{LO}$, $f_{IF} = f_{RF} - f_{LO}$ If $f_{RF} < f_{LO}$, $f_{RF} < f_{LO}$, $f_{IF} = f_{LO} - f_{RF}$[3,10]. If one of these is at the desired signal frequency, then the other is the Image frequency. Signals and receiver noise that appear at the image frequency need to be rejected using either RF filters or an image reject mixer. Since the mixer is a nonlinear device it can produce inter-modulation products at other frequencies called spurious responses. These occur for any RF signals that satisfy the condition $mf_{RF} + nf_{LO} = f_{IF}$, where $m$ and $n$ are integers. The third order inter-modulation product affects the dynamic range of the receiver. The advantages of image rejection mixer are high dynamic range, good linearity, good VSWR, low inter-modulation products and less susceptibility to burnout[17].

The three channel image rejection mixer (IRM) is designed for C-Band frequency. The general function of IRM is a receiver's front-end mixer/filter, which must greatly attenuate the image frequency[4]. The IRM differs from common balanced mixer by its capability of suppressing of signals and noises coming from an image channel[5,10]. The mixer utilize two standard double balanced mixer cells and a 90° hybrid fabricated in a GaAs MESFET process. A low frequency quadrature hybrid was used to produce a 100 MHz IF-output. The IRM is a highly sensitive, low noise unit. The LO is fed through the 4-way power divider which is in-house designed using Wilkinson technique[7]. Three ports of the power divider are used for the three channels. Fourth port is used for the LO monitoring.

Table 2 shows achieved parameters value of IRM three channel mixer at three different frequencies. This table revels that noise figure 6.8 dB, P1dB compression is 9 dBm, image rejection 25 dB min and operated by +15 V supply.

**Table 2. Achievable parameters value of IRM three channel mixer at different frequencies**

| RFFREQUENCY | 5.405 GHz | | | 5.505 GHz | | | 5.605 GHz | | |
|---|---|---|---|---|---|---|---|---|---|
| | CH-A | CH-B | CH-C | CH-A | CH-B | CH-C | CH-A | CH-B | CH-C |
| LO Freqency (GHz) | 5.375 | 5.375 | 5.375 | 5.475 | 5.475 | 5.475 | 5.575 | 5.575 | 5.575 |
| LO Power (dBm) | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 | 13 |
| RF Power (dBm) | -20 | -20 | -20 | -20 | -20 | -20 | -20 | -20 | -20 |
| IF Out (dBm) | 2.996 | 2.770 | 2.870 | 2.450 | 2.500 | 2.920 | 2.510 | 2.580 | 2.78 |
| Variation (-5 MHz) | 2.870 | 2.320 | 2.620 | 2.300 | 2.400 | 2.690 | 2.650 | 2.380 | 2.55 |
| Variation (+5 MHz) | 2.710 | 2.320 | 2.770 | 2.430 | 2.420 | 2.820 | 2.480 | 2.400 | 2.79 |
| RF Image Frequency | 5.345 | 5.345 | 5.345 | 5.445 | 5.445 | 5.445 | 5.545 | 5.545 | 5.545 |
| Image Rejection | -25.2 | -24.0 | -25.5 | -25.2 | -23.6 | -25.6 | -25.3 | -23.7 | -26.3 |
| Noise Figure (dB) | 6.360 | 6.840 | 6.690 | 6.330 | 6.900 | 6.630 | 6.320 | 6.890 | 6.64 |
| P1dB (dBm) | 9.0 | 9.070 | 9.10 | 8.910 | 8.810 | 8.900 | 8.900 | 9.00 | 9.00 |
| RF in VSWR | 1.210 | 1.540 | 1.320 | 1.170 | 1.510 | 1.390 | 1.140 | 1.460 | 1.31 |

### 3.7 Advantages of Components Used

The values of the hardware components are explained above which are used in the newly design front-end are selected such a way that the crucial parameters like sensitivity, dynamic range, noise figure, gain, phase noise and power consumption are superior to existing one. The major parameters like noise figure of LNA 1.1 dB, phase noise of LO -87 dBc/Hz, mixer image rejection 25 dB, isolator isolation 35 dB, direction coupler coupling factor 20 dB have been selected. This will lead to the enhancement of both angle and range accuracy of the monopulse tracking radar. Apart from this the target detection range and target tracking range are increased immensely, which are the first and foremost requirements the test range scenario.

## 4. RESULTS AND DISCUSSIONS

The RF signal fed from STAMO to SPDT switch of level 0 dBm and frequency of C-band and modulated with 1 μs and PRF of 585.5 Hz as a radar signal. The 30 MHz IF spectrum is measured by FSP7 spectrum analyzer with setting VBW 30 Hz, RBW 30 KHz, span 5 MHz and output power -42.39 dBm is given in Fig. 3. The radar sync is fed to the switch from the Function generator model No 33250 make Agilent. The output of sync is monitored by the digital storage oscilloscope model DSO9104A make Agilent.

Figure 3 also shows overall noise figure and gain of the newly designed C-band RF front-end. The overall noise figure of the system is excellent that is coming around 2.5 dB compare to the existing RF front-end which has 5.4 dB. The gain is also very good compare to the existing RF front-end. This figure also shows the noise figure and gain at different frequencies and the value is varying from 2.4 dB to 2.5 dB in the entire IF bandwidth. The measurement has been carried out with

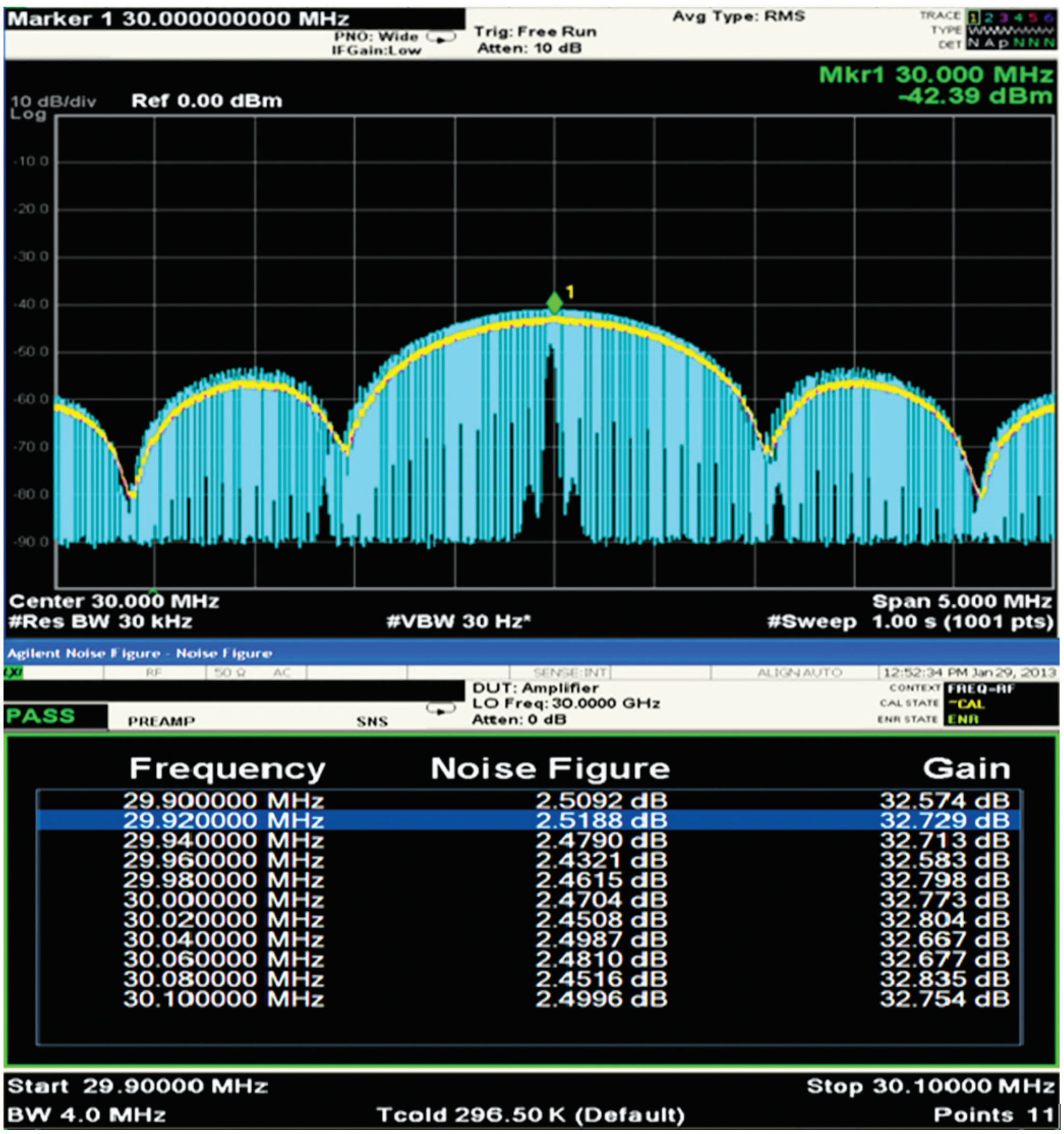


**Figure 3. Intermediate frequency (IF) output spectrum, overall noise figure (NF) and gain of the newly designed front-end.**

a noise source model N4000A, SNR 6 dB series noise source (SNS) make Agilent with the EXA signal analyzer model N9010A and make Agilent[18,20] with settings BW = 4 MHz, $T_{cold}$ = 296.5 K and points 11.

The LO conditioner output phase noise is shown in Fig. 4. The phase noise is -87 dBc/Hz with the frequency offset of 10.3 KHz is far better than the existing LO of -70 dBc/Hz[7,8]. The figure also shows the different phase noise values at different frequency offsets. The Phase noise is measured by the EXA signal analyzer model N9010A make Agilent[18,19] with carrier frequency 5.47 GHz and carrier power 23.5 dBm.

The sensitivity is -85 dBm is much higher compare to the existing front-end which has -82.6 dBm. This measurement has been carried out by the signal analyzer with model No.N9010A make Agilent[18]. The dynamic range of the receiver is 76 dB, which is much higher compare to the existing front end of 60 dB.

The three IF-outputs of the proposed C-band front-end are well gain and phase matched. The measurements were carried out with respect to the SUM channel as a reference. The gain ratios come around 1 dB and the

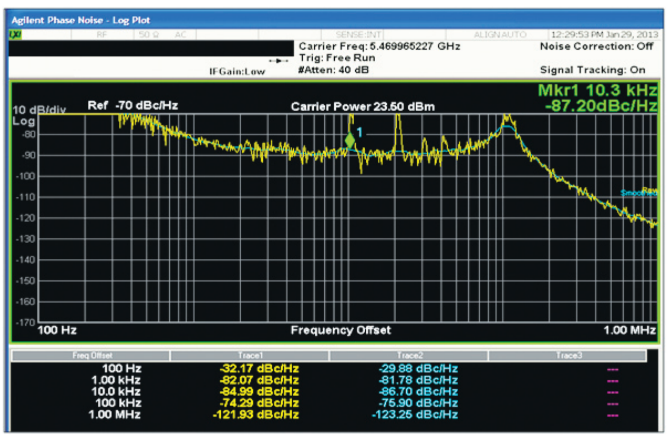


**Figure 4. Phase noise of local oscillator at different frequency offset.**

phase difference among the channels is 4° which is better than the existing gain ratio 1.5 dB and phase difference 10°. The gain ratio and phase difference are measure by the vector volt meter and vector network analyzer. The vector volt meter is used of model no.8508A and make HP. The vector network analyzer is used of model E8362B make Agilent[21]. Gain ratio and phase difference among the channels measured by vector volt meter at IF frequency 30 MHz. The phase of channel A and channel B can also measured by Vector network analyzer (VNA). A special circuitry has been designed for measurement of phase using VNA. The phase between channel A and Channel C is 4° which is quite less than the existing front end of 10° at IF frequency 30 MHz. The phase difference is measured by VNA as well as vector voltmeter and the results are very closely matching.

This new design of front end consumes significantly less power, low phase noise of LO, low Noise Figure, high gain, high sensitivity and higher target tracking range in skin as well as transponder mode compared to the existing front end. These overall improved performance comparison matrix is given in Table 3.

The mixed mode of operation (skin and transponder) is possible in this configuration. The LO can be tuned to multi-frequencies with some delay. The difference between two frequencies can be adjusted in accordance with transponder delay by the computer program. Skin mode of tracking the LO is tuned to a frequency $F_1$ and for transponder tracking it is tuned to $F_2$. The inherent delay of the transponder return is 7.1 µs. These two frequencies of the LO can be tuned with delay of 7.1 µs (1.05 km) by the computer program. As a result the two signals (skin and transponder) of range difference 1.05 km are detected in the radar range display simultaneously. Figure 5 shows radar range display of skin and transponder signal with two LO frequency $F_1$ and $F_2$ separated by 7.1 µs delay which corresponds to 1.05 km.

**Table 3. Performance comparison matrix.**

| Parameters | Existing RF front-end | | Newly design front-end | |
|---|---|---|---|---|
| Power consumption | 50 W | | 28 W | |
| Noise figure | 5.4 dB | | 2.5 dB | |
| Gain | 27 dB | | 32.729 dB | |
| Sensitivity of RF Front end for 400 MHz BW | -82.6 dBm | | -85 dBm | |
| Dynamic range | 60 dB | | 76 dB | |
| Gain ratio | 1.5 dB | | 1 dB | |
| Phase difference | 10° | | 4° | |
| LO phase noise | -70 dBc/Hz | | -87 dBc/Hz | |
| LO output power | 16 dBm | | 26.5 dBm | |
| Tracking range enhancement | Skin<br>90 km for 1 $m^2$<br>target @ 16 dB SNR | Beacon<br>1660 km for<br>100 W beacon | Skin<br>120 km for 1 $m^2$<br>target @ 16dB SNR | Beacon<br>2200 km for<br>100 W beacon |

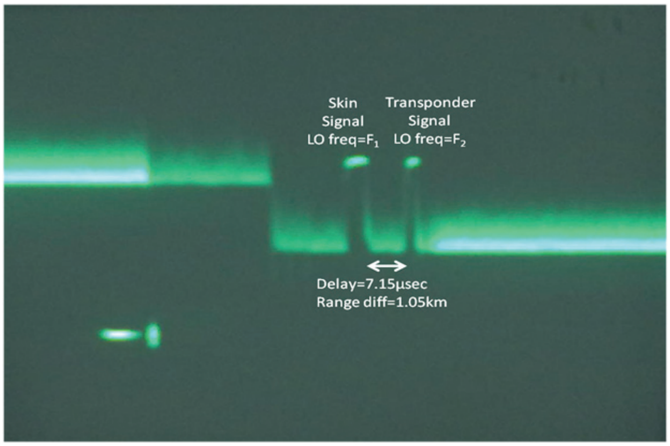


**Figure 5. Radar range display of skin and transponder signals (mixed mode).**

## 5. CONCLUSIONS

The newly designed C-band front-end is much better performance than the existing C-band front-end of PCMC radar. All the important parameters are better compare to the existing RF front-end**.** Since all the important parameters are demonstrated and measured. The hardware complication has already been eliminated by housing total RF front-end in one box instead of many boxes as in the existing front-end of PCMC radar. The simulation facility has been incorporated so that the range calibration and receiver health status can be ascertained. Since the local oscillator conditioner is housed in the front-end assembly, the overall losses reduced drastically, as compare to the existing front-end. The newly designed LO is highly stable and its amplitude, frequency and delay between skin and transponder frequency can be controlled digitally with PC. Therefore the AGC calibration and the mixed mode operation of receiver (skin and transponder) can be carried out easily compare to the existing front-end.

A variable attenuator is incorporated to enhance the dynamic range and prevent the receiver saturation while reflection comes from nearby targets. The power consumption is reduced remarkably with this new front end design. Integrating this front-end module to the PCMC radar, the overall performance, accuracy, reliability, availability and radar tracking range enhanced quite appreciably.

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## CONTRIBUTOR

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