Design of RF Receiver Front-end Subsystems with Low Noise Amplifier and Active Mixer for Intelligent Transportation Systems Application

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ABSTRACT

This paper presents the design, simulation, and characterization of a novel low-noise amplifier (LNA) and active mixer for intelligent transportation system applications. A low noise amplifier is the key component of RF receiver systems. Design, simulation, and characterization of LNA have been performed to obtain the optimum value of noise figure, gain and reflection coefficient. Proposed LNA achieves measured voltage gains of ~18 dB, reflection coefficients of -20 dB, and noise figures of ~2 dB at 5.9 GHz, respectively. The active mixer is a better choice for a modern receiver system over a passive mixer. Key sight advanced design system in conjunction with the electromagnetic simulation tool, has been to obtain the optimal conversion gain and noise figure of the active mixer. The lower and upper resonant frequencies of mixer have been obtained at 2.45 GHz and 5.25 GHz, respectively. The measured conversion gains at lower and upper frequencies are 12 dB and 10.2 dB, respectively. The measured noise figures at lower and upper frequencies are 5.8 dB and 6.5 dB, respectively. The measured mixer interception point at lower and upper frequencies are 3.9 dBm and 4.2 dBm.

Keywords: Active mixer; Intelligent transportation systems; Low noise amplifier

1. INTRODUCTION

Since the past decade, there has been explosive growth in the traffic on the roads. Accordingly, the rate of accidents is also increased proportionately. Intelligent transportation systems (ITS) have modified the concept of vehicles, which are becoming part of a global transport network. Systems for collision avoidance to alleviate congestion are being integrated into the vehicles for improvement of safety and security[1-2]. LNA is a part of low noise receiving systems for vehicle location tracking in ITS[2]. In an RF receiver, the LNA is the first main component[3]. Figure 1 shows the system setup of a possible RF receiver architecture for ITS application.

As shown in Fig. 1, the basic building blocks of the wireless transceiver are: Filter, coupler, diplexer, LNA, power amplifiers, mixers, and oscillators LNA is used to amplify the signal while suppressing noise in the received signal[4-5]. Ultra-wideband (UWB) LNA for ITS applications has been presented[6]. A distributed amplifier with relatively good performance is reported by Chang & Lin[7]. A penta-band LNA has been designed for inter-vehicle communication[8]. Tripathi[9], *et al.* has reported subsystems for vehicle location tracking for an integrated vehicle communication system. LNAs working on selective band of frequencies have been explained[10-11].

A mixer is another important part of the wireless communication system. Multifunctional components such as

noise and nonlinearity modeling of active mixers for fast and accurate estimation are highly required to reduce the overall number of components in a radio receiver[11]. A wideband CMOS active mixer has been reported[12]. A direct-conversion mixer with low flicker noise and low DC offset is presented for WLAN applications[13]. The concept of multiband and multi-standard transceiver architectures has revolutionized the field of wireless communications. In RF circuits, each of these individual building blocks may be implemented to give a dual-band performance or it is also possible to have a part of
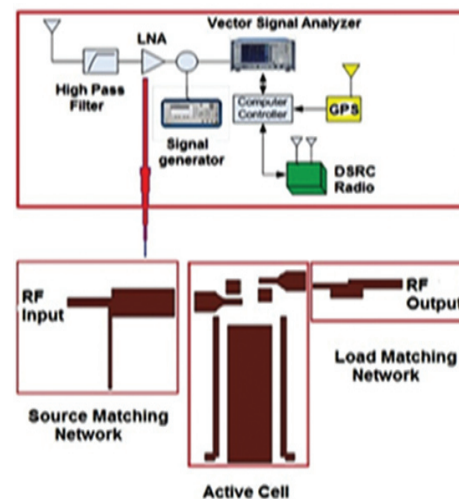

Figure 1. Receiver architecture for ITS application.

the circuit performing dual-band operation and the remaining components may be optimized to work on an individual frequency thereby achieving a balance between space constraints and optimization[14-18]. A dual-band CMOS front-end for a wireless LAN application has been reported[19]. An active flicker noise and mismatch up-converting active mixer with odd cascade switching pairs that require lower switching frequencies have been reported[20]. Linearization technique using interaction between two nonlinear systems for active mixers is reported in[21]. A low-noise mixer using a switched biasing technique for WLAN systems at 5.8 GHz has been presented[22]. Implementing Intelligent Traffic Control System for Congestion Control has been described[23]. The different development of active integrated circuit mixer for wireless transmitter application has been reported in the context of vehicular communication and ITS[24-27]. The problems of choice of road route under conditions of uncertainty which drivers are faced with as they carry out their task of transportation have been described[28]. A green vehicle distribution model in a public transportation network has been reported[29]. A model developed to optimize the implementation of EFV vehicles on the existing road network taking into account air pollution, noise level and operating and user costs have been presented[30]. A new approach for cost and risk assessment in the multi-objective selection of routes for the transport of hazardous materials (hazmat) on a network of city roads, The RF integrated circuits have drawn significant research attention due to the current trend toward compact, more power efficient RF front-ends, and exploitation of frequency reuse in commercial and military systems. In order to further reduce circuit size, space/volume of RF system, manufacturing cost etc, is reported in[31-36].

This paper reports a novel design, analysis, and characterization of microstrip RF receiver front-end subsystems with low noise amplifier and active mixer for ITS application. A new matching network for applications intended for ITS application. A microstrip pHEMT based LNA is designed at 5.9 GHz. Gain and noise figure of the proposed LNA is ~18 dB and ~2 dB. The reflection coefficient is -20 dB and power consumption is 30 mW. The bias network is changed to a self-bias circuit for obtaining the designed current. For, V_{DS} = 2.4V, I_{DS}=12 mA and V_{GS}=0.2 V. Wideband architecture is used in the implementation of this mixer which operates at 2.43 GHz as well as 5.25 GHz. In mixer IF=300 MHz, The measured conversion gain and the noise figure of the active mixer at 2.43 GHz is 12 dB, 5.8 dB, and at 5.2 GHz conversion gain is 10.2 and noise figure 6.5 respectively. The measured mixer Interception Point (IIP3) at lower and upper frequencies are 3.9 and 4.2 d_Bm. The bias network of circuit for obtaining the designed current is V_{DS}= 2V, I_D = 10 mA, R_G=2.2 KΩ and R_D=225Ω.

2. THEORY AND DESIGN OF LNA

Figure 2 shows the systematic steps for designing low noise amplifier:
(i) First, we select an active element.
(ii) Select the DC bias operating point.
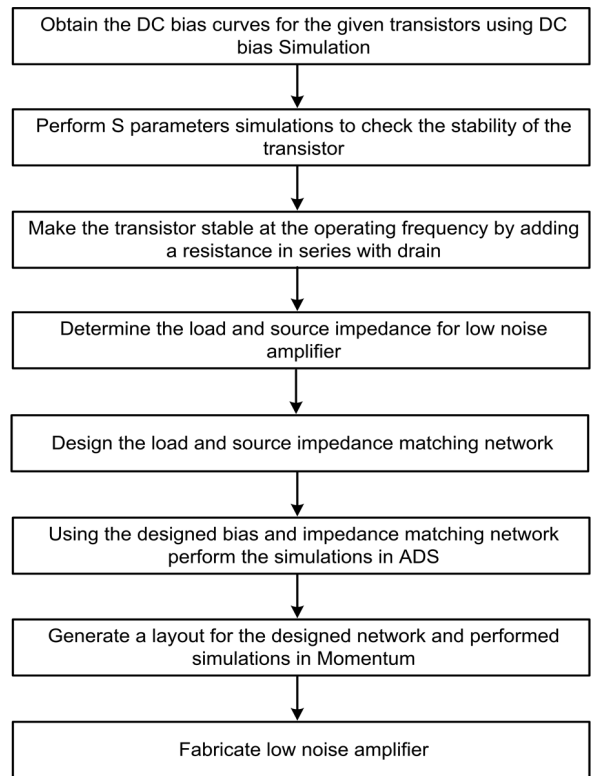(iii) S-parameter simulation to check the stability of the transistor.

Figure 2. Design flow chart.

(iv) Determine the load and source impedance for low noise and optimal gain.
(v) Design the source and load impedance matching network.

These design steps have been followed in ADS and momentum simulations. The design of LNA includes active cell, input matching network and output matching network at 5.9 GHz for DSRC/ITS applications.

As an active component, a bipolar junction transistor (BJT) has been used at microwave frequencies. The launch of field-effect transistors (ATF36163) revealed the capabilities of higher gain and lower NF. Nowadays, pHEMT are utilized to provide low NF and high gain. A suitable dc bias is ensured in order to provide high gain and stability. The amplifier stability depends on Rollet's stability factor, k defined as

$$k = \frac{1 - |S_{11}|^2 - |S_{22}|^2 - |\Delta|^2}{2|S_{11}||S_{22}|} \qquad (1)$$

where, $\Delta = |S_{11}S_{22}S_{12}S_{21}|$

The microstrip line based matching networks have been designed. It involves the calculations of reflection coefficients at the source end and the load end of the transistor with active cell network. The transmission line sections and stubs are used to provide the matching network, which allows 50 Ω characteristic impedance at transmitter terminals. Here, Z_L is the load impedance. It is converted to Z_B by the first series transmission line section of length L_2 and an open-circuited shunt stub of length S_2. This impedance is further converted into standard impedance Z_0 by another series transmission line section of length L_1 and an open-ended shunt stub of length

S_1. Here, the characteristic impedances of all transmission line sections and stubs are set to standard 50Ω.

3. MEASUREMENT AND ANALYSIS

Key sight ADS[26] tool is used for the design and analysis of the cascaded LNA simulation. The LNA is designed with the ATF-36163 which draws 12 mA from the 2.4V supply. We are achieve noise factor less then ~2 dB, gain more than ~18 dB with good return loss -20 dB over the desired bands. Figure 3 shows the fabricated prototype of LNA. The LNA is printed on the top of the Rogers/RT duroid as the substrate material having a thickness of 1.524 mm and $\varepsilon_r = 3.2$. Figures 4 (a & b) shows simulated and measured input and output return loss of proposed LNA. Figure 4(c) shows the measured and simulated responses of proposed gain of amplifier. Figure 4(d) shows simulated and measured noise figure performance of LNA. The observed loss below 20 dB at 5.9 GHz, ITS bands confirms the successful design of our input and output matching network.
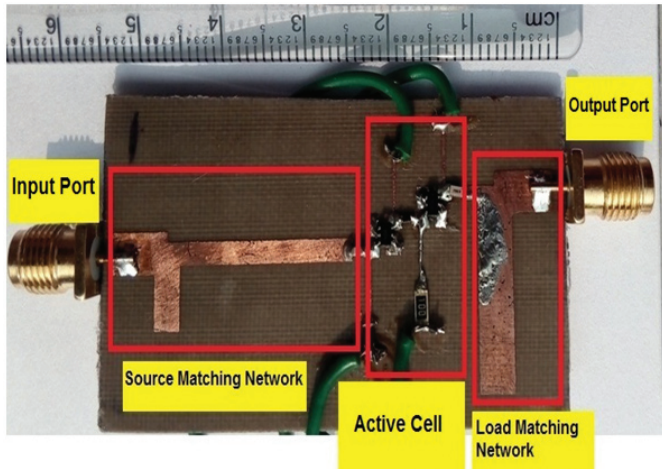

**Figure 3. Fabricated low noise amplifier.**

4. THEORY AND DESIGN OF MIXER

Design and development of active integrated and broadband circuit mixer for use at 2.4 GHz and 5.25 GHz. Active mixers use active devices to translate frequency as well as providing amplification to the translated signal. An active mixer can be designed using bipolar junction transistor (BJT) or field effect transistor (FET). However, FET is preferred due to its better noise characteristics. The transconductance has strongest non-linearity component and therefore it is used in the implementation of mixer in this work. The drain current $i_d(t)$ of FET can be expressed as:
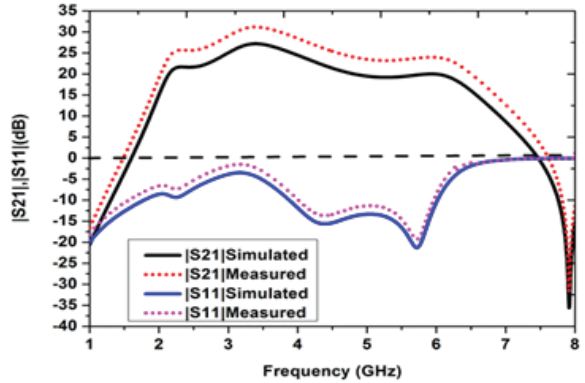
$$i_d(t) = g(t)V_g(t) \tag{2}$$

where $g(t)$ is the transconductance of the device and $V_g(t)$ is the gate voltage. Since the output signal provided by a local oscillator (LO) is quite large, therefore a large signal analysis has been performed. The LO pumped FET transconductance can be expressed as a Fourier series in terms of the harmonics of the LO signal as:
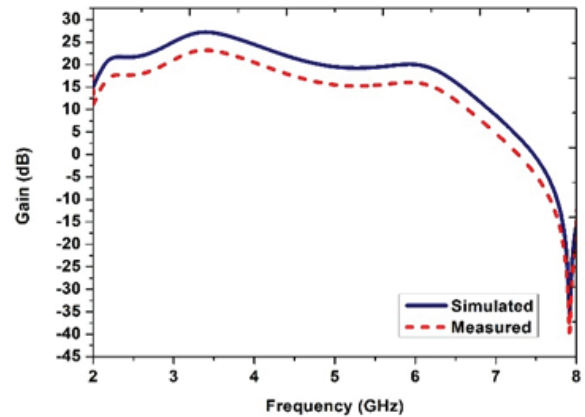
$$g(t) = g_0 + 2\sum g_n \cos n\omega_{LO}t \tag{3}$$
$$n = 1,2,\dots \infty$$
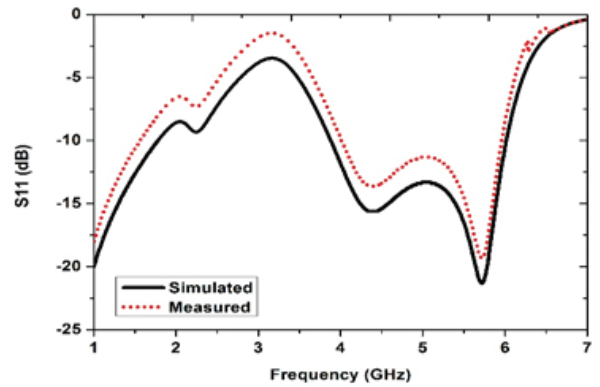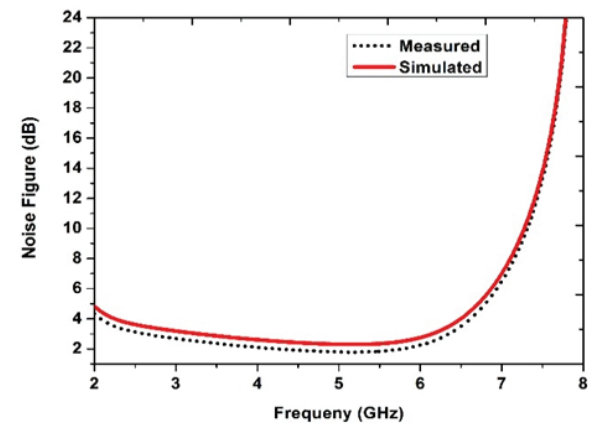

Figure 4. **(a)** Return loss of LNA, **(b)** Performance of the LNA, **(c)** Noise figure analysis, and **(d)** LNA Noise figure analysis.

Suppose the input RF signal at the gate is:

$$V_g(t) = V_{RF} \cos n w_{RF} t \qquad (4)$$

Then, Eqn. (1) can be written as:

$$
\begin{aligned}
i_d(t) = {} & g_o V_{RF} \cos(n\omega_{RF} t) + \\
& g_1 V_{RF} \left[\cos(\omega_{RF} - \omega_{LO})t + \cos(\omega_{RF} - \omega_{LO})t \right] + \\
& g_2 V_{RF} \left[\cos(\omega_{RF} - 2\omega_{LO})t + \cos(\omega_{RF} - 2\omega_{LO})t \right]
\end{aligned} \qquad (5)
$$

As can be seen from Eqn. (3), the desired down-conversion term is due to the $n=1$ term of the Fourier series. Therefore, the only significant co-efficient is g_1.

5. DESIGN METHODOLOGY OF ACTIVE MIXER

The full-wave analysis is the most accurate form of analysis of a design. It is set to include all the parasitic and stray losses that might occur in the circuit. This simulation is carried out after drawing the layout. The mixer has been tested using a spectrum analyzer. The spectrum is similar in the entire operating frequency range i.e. 1-6 GHz. The circuit also caters for a minor shift in the incoming RF frequency as the IF is still detected at 295 MHz and 305 MHz as well. Though an IF is detectable in the spectrum, the power obtained at the output shows a conversion loss instead of a conversion gain. The reason for this is the fabrication error introduced. The fabrication error has been detected in the actual fabricated mixer. In Fig. 5 the commonly used bias circuit is shown and its performance parameters are RF bandwidth, insertion loss and a mismatch at the two RF ports and the maximum DC current depending on the device being used.
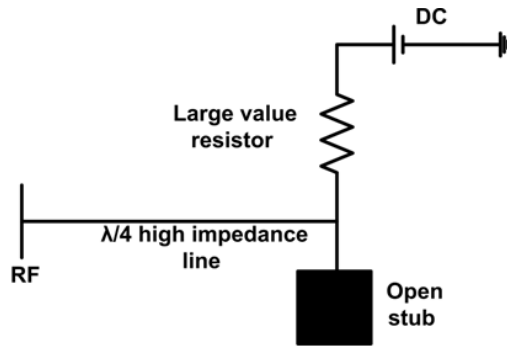

Figure 5. Bias network in microstrip.

The most obvious method of biasing FET is to supply separate DC voltages to the gate and drain terminals such that the gate supply can be varied i.e. it is adjustable. In practice, the gate supply is usually a fixed DC voltage source varied by employing an appropriate resistor divider network to supply the required gate voltage. The source is grounded in this case. The maximum gain is obtained from a FET when the source is grounded and hence, this is preferred if high efficiency is required.

The topology of HEMT based broad band mixer for dual-band operation is shown in Fig. 6. The mixer is designed to operate as a transconductance mixer and hence, the operating point is chosen as $V_{DS} = 2$ V, $I_{DS} = 10$ mA ($V_{GS} = -0.3$ V). A shunt gate resistor of 100 Ω is used to stabilize the transistor and providing gate bias. Moreover, it prevents oscillations
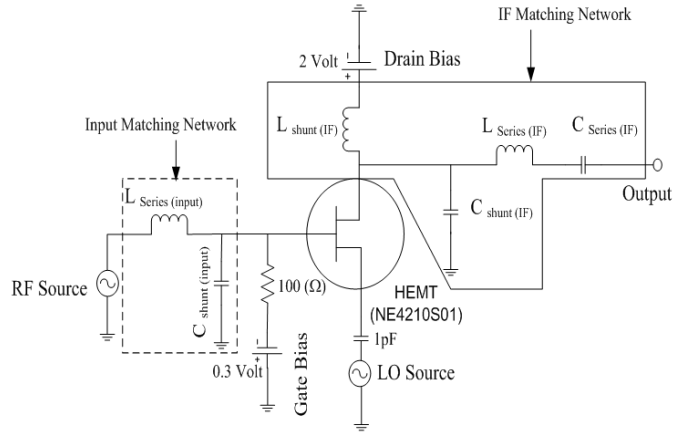

Figure 6. HEMT based mixer for dual band operation.

by effectively cancelling out the negative resistance of the active device. Designing the matching networks for mixer is a very important issue in mixer design. For the input matching network, the input impedance has to be determined at RF while short-circuiting the IF. The LO signal is very close to the RF signal and hence, to obtain the input impedance, LO signal cannot be shorted at the input terminal. Instead, the IF is shorted at the input and optimization has to be carried out to match the input. The bias networks designed for 2.45 GHz and 5.25 GHz and their dimension are given below in Tables 1-4.

Dimensions (in mm) of the proposed Mixer for Dual Band Operation.

Table 1. Line dimension of 2.45 GHz Bias Network

Zo (Ω)	W (mm)	L (mm)
50	0.759	2.5(arbitrary)
100	0.204023	23.7634

Table 2. Radial stub dimension in 2.4 GHz bias network (post tuning)

α(degrees)	r_1 (mm)	r_2 (mm)
66	0.8	13.9272

Table 3. Line dimension of 5.25 GHz bias network

Zo (Ω)	W (mm)	L (mm)
50	0.759	2.5(arbitrary)
100	0.204018	13.9272

Table 4. Radial stub dimension in 5.25 GHz bias network (post tuning)

α(degrees)	r_1 (mm)	r_2 (mm)
66	0.3	6.92716

5.1 Design of Matching Network

To design the matching networks for mixer, we have to determine the input and output impedances for active device[14-15]. For this purpose, we have to short circuit the IF at the RF input side and the RF and LO at the IF output side. For the

input matching network, the input impedance has to be determined at RF while short-circuiting the IF. The LO signal is very close to the RF signal and hence, to obtain the input impedance, LO signal cannot be shorted at the input terminal. Instead, the IF is shorted at the input and optimization has to be carried out to match the input impedance obtained at RF to 50 Ω of the input line impedance. Thus, the impedance seen at each frequency is different for each terminal. For the output matching network, the output impedance has to be determined at IF while short-circuiting all RF and LO signals.

The output matching network has to match the impedance calculated at IF to the output 50 Ω output line impedance. This impedance calculation was done with the help of Key Sight ADS 2016[17]. The computed impedances are shown in Table 5.

Table 5. Computed Impedances at RF and IF

Freq. (GHz)	ZRF (Ω)	ZIF (Ω)
0.140	(0.99)- (2.457×10-4)	(934.097)-j(147.322)
0.300	(0.99)-j(3.561×10-4)	(859.830)-j(285)
2.4	(83.25)-j(21.251)	(1.0-j0.003)
4.0	(72.717)-j(30.371)	(0.999-j0.005)
5.25	(63.811)-j(33.985)	(0.999-j0.006)

The element values of the optimized matching network for this mixer are given in Table 6.

The conversion gain and noise figure are obtained using ADS Momentum in conjunction with circuit simulator. The lumped elements in the mixer circuit are transformed to distributed circuits and layout simulations are performed using ADS Momentum. The internal port boundary conditions are used in e. m. simulation to include the effect of lumped elements such as a resistor, capacitor, inductor, and transistor in the circuit. The simulated layout is shown in Fig. 9. The parallel architecture = 300 MHz, Transistor used: NE4210S01 pHEMT (operating range: 2- 18 GHz). The proposed fabricated active mixer structure has been shown in Fig. 7. It consists of a substrate (Rogers Duroid 5880) having dielectric constant εr = 2.2 and thickness h = 0.254 mm.

6. RESULT AND ANALYSIS

The nonlinear harmonic balance analysis (implemented in key sight ADS 2016) was used to compute the conversion gain and noise figure of the designed mixer. The variation in conversion gain of the mixer with RF power and LO power is shown in Figs. 8 and 9. The variation in conversion gain of the mixer with RF and LO power obtained from full-wave nonlinear analysis is shown in Figs. 9 and 10. The general parameters of an active mixer are conversion gain, harmonic distortion, noise figure, isolation of RF to LO isolation, as well as leakage of LO and RF signals into the IF output.

The performance mainly depends on DC bias, the source feedback, and the quality of the drain short circuit.

Table 6. Components values of impedance matching networks

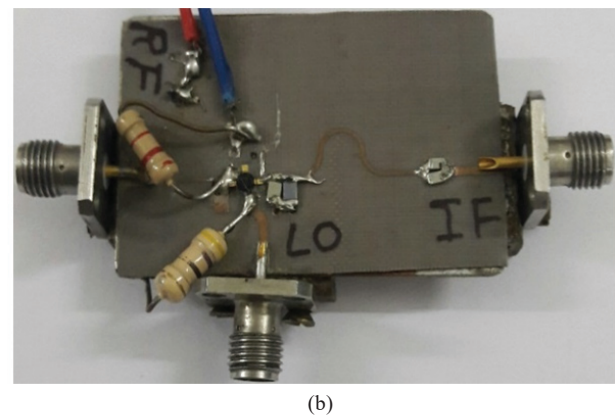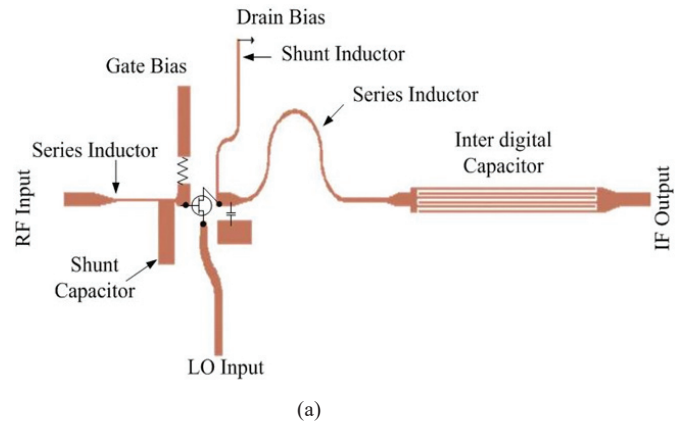| Input impedance matching networks (2-6GHz)	*f* = (2-6 GHz)	
	L (series input) = 1.671nH, C (shunt input) = 0.583pF	
IF matching networks	f = 300 MHz	f = 140 MHz
	L shunt (IF) = 3.9 nH C shunt (IF) = 70 pF L series (IF) = 8.28 nH C series (IF) = 2.32 pF	L shunt (IF) = 10 nH C shunt (IF) =124.37 pF L series (IF) = 16.5 nH C series (IF) = 5 pF

(a)

(b)

Figure 7. (a) Layout of active mixer used in the full-wave simulation and (b) Fabricated prototype of HEMT based mixer for dual band operation.
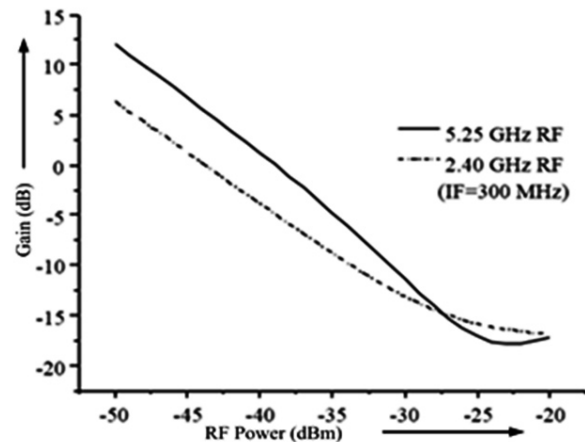

Figure 8. Variation in mixer conversion gain with RF power (circuit simulation).

The LO level is set high to obtain maximum gain. The source feedback decides the LO level and oscillation condition. The measured active mixer Interception Point (IIP3) at lower and upper frequencies are 3.9 and 4.2 dBm. The HEMT based active mixer results obtained from circuit simulation and full-wave simulation are given in Table 7. Finally, Tabl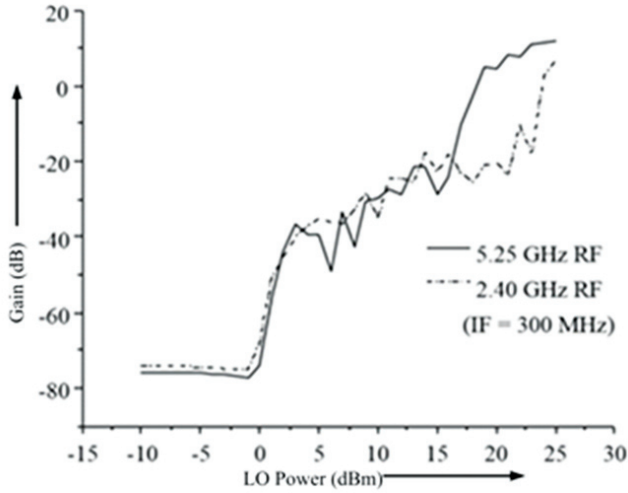es 8 and 9 compares the measured performance of our LNA and Mixer with other similar reported works. Proposed devices finds applications in multiband RF front-ends and software-defined radios. To author's knowledge, the investigation of concurrent LNA and dual-band Mixer for highly improving the level of integration of the receivers is presented for the first time.

Figure 9. Variation in mixer conversion gain with LO power (circuit simulation).
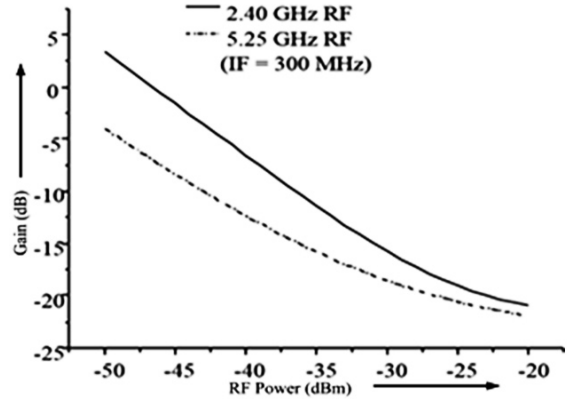
Figure 10. Variation in mixer conversion gain with RF power (full wave simulation).

Table 7. HEMT based active mixer (IF=300 GHz)

Mixer parameter	Circuit simulation		Measurements	
	RF = 2.45 GHz	RF = 5.25 GHz	RF = 2.45 GHz	RF = 5.25 GHz
Conversion gain (dB)	13.372	12.059	12	10.2
Noise figure (dB)	5.25	6.44	5.8	6.5

Table 9. Performance comparison with previously published mixers

Parameters	[13]	[14]	[21]	[22]	[35]	This work
Pass band centre frequency (GHz)	5	5.2	2	2.4	2	2.4/5.25
Gain (dB)	11	11	7.2	10	8	12/10.2
Noise figure (dB)	7	10	7.2	13.2	17	5.8/6.5
RF power (dBm)	30	30	22	23	19	26/28
Power consumption (mW)	25.5	8.7	7.7	4	8	27/30
Interception point (IIP3) (dBm)	2.5	-10.5	3.7	17.1	12	3.9/4.2

Table 8. Performance comparison of proposed LNA with other reported works

Parameters	[4] Simulation	[5] Measured	[6] Simulation	[7] Measured	[32] Measured	This work (Measured)
Technology used	FHX76LP Low noise Super HEMT microstrip technology	Microstrip, €r = 3.2, H=1.524 mm	0.18µm CMOS technology	0.18µm CMOS technology	Microstrip, €r = 3.0, H=0.508 mm	Microstrip, €r = 3.2, H=1.524 mm
Pass band center frequency (GHz)	5.75-5.85GHz	2.44 GHz, 5.25 GHz	3.1 GHz,	7 GHz	2.5 GHz, 5 GHz	5.9 GHz
Gain (dB)	>10dB	7.15 dB & 7.8 dB	12.1 dB	8 dB	1.8 dB 5.4 dB	18 dB
Noise Figure (dB)	<10dB	4.34 dB 4.69 dB	2.4 dB	3.46 dB	2.4 dB 3.0 dB	2 dB
Return loss (dB)	<-10dB	10.5 dB 16 dB	< -7.5 dB	<-10dB	12 dB 11 dB	-20 dB
Power Consumption	4.5mW	35.1 mW	7.7mW	46.85 mW	28 mW	30 mW
Size	-	1.11λg x 0.85λg	-	-	0.96λg × 0.34λg	1.1λg× 0.75λg
Control voltages	2	N/A	1.8	3	1	2.4
Stopband attenuation	<-11dB	-40 dB	-11dB	-28.6 dB	-45 dB	-40 dB
Selectivity	Average	Good	Average	Good	Better	Better

7. CONCLUSION

RF Receiver Front-End subsystems such as low noise amplifier and active mixer for vehicular communication/ITS applications have been designed, simulated and experimentally characterized. In this article, LNA is an essential part of an RF receiver front-end system for intelligent transportation system applications. The simulated and measured gain of amplifier is ~18 dB and noise figures is ~2 dB at 5.9 GHz, respectively. Nonlinear analysis of HEMT based active mixer has been carried out using commercially available circuit simulator alone as well as circuit simulator in combination with electromagnetic simulator. A wideband mixer has been designed and implemented in microstrip for 300 MHz IF. The measurement results of active mixer show that conversion gain is 12 dB and the noise figure is 5.8 dB at 2.45 GHz, whereas conversion gain is 10.2 dB and noise figure is 6.5 dB at 5.25 GHz. The measured active mixer Interception Point (IIP3) at lower and upper frequencies are 3.9 dBm and 4.2 dBm, respectively. This multifunctional system will be of reduced size and consume less power. As a part of the future work, we have to develop an integrated vehicle communication system using our own customized subsystems for transceiver module.

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