Design of Low Noise Amplifier with Active Integrated Antenna at 5 GHz

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Abstract **-** An Active Integrated Antenna with Low Noise Amplifier (ALNA) at 5 GHz has been designed and developed for wireless communications. The design achieves a low noise figure by directly integrating a low noise amplifier to a dual layered microstrip close proximity coupled patch antenna at 5 GHz. Measured results show a noise figure (NF) of 1.22 dB, an excellent return loss of greater than 12 dB and good impedance matching which resulted in a bandwidth of about 10% for the active device. This paper presents the methodology, simulations and experimental works carried out in accomplishing the above objective. LINC2 and Microwave Office software were used to simulate and find the optimum design and results.

Keywords: Active Integrated Antenna; Low Noise Amplifier; micostrip antenna; proximity coupled feed.

1. Introduction

The recent migration and upsurge in the demand for portable wireless communication products for the 5 GHz WLAN applications has caused much research interest in AIA technology where the passive antenna is integrated with an active device in the front-end of RF systems. In this project, a close proximity coupled microstrip antenna is directly integrated with a low noise amplifier (LNA) to produce an AIA system to achieve low noise. Similar, investigations have been done at 2.4 GHz, however, the ALNA at 5 GHz is able to demonstrate both linear and circular polarizations as well as a low noise figure.

Even though this technology has provided a lot of attraction and avenue, there are still many technical hurdles like the availability of inexpensive good quality dielectric substrates (materials with tight dielectric tolerance, loss tangent, and good mechanical properties) and antenna miniaturization that need to be overcome before a low noise receive antenna can be realized at 5 GHz by combining the receiver function through an LNA into a dual-layered microstrip patch antenna.

In this paper, the focus of the study is to improve the NF by direct connection of the system impedance of 50 Ω. The impedance matching network has been designed to transform the antenna feed point impedance to the impedance required at the input to the amplifier. This is done so that the antenna presents an input impedance to the amplifier corresponding to the "optimum noise impedance" which requires the source reflection coefficient, Γ_s of the antenna seen from the amplifier input, equals Γ_{opt} at the frequency of interest. Γ_{opt} is the reflection coefficient corresponding to the optimum noise impedance [1]. The underlying theory for this being that minimum NF is achieved when $\Gamma_s = \Gamma_{opt}$. The close proximity coupled antenna (CPPA) feed point impedance in this project is first tuned to 50 Ω to simplify the design of the required impedance matching network. The input circuit of the LNA is then matched to the CPPA using a series stub to achieve a 50 Ω common interface to obtain the best NF.

2. Design Consideration

2.1 Passive Close Proximity Coupled Patch Antenna

The choice of the substrate is an important aspect in the design of the antenna. The substrate chosen for the antenna must be thick, t_1 with a low permittivity to provide better efficiency, larger bandwidth and better radiation whilst the substrate for the feedline and circuitry must be thin, t_2 with a higher dielectric to minimize undesired radiation and coupling [2]. The Rogers Corporation's RT Duroid 5780 ($\varepsilon_{r1} = 2.33$, t_1= 125 mils) was selected for the patch while a thinner FR4 substrate ($\varepsilon_{r2} = 4.7$, t_2= 63 mils) was used for the feedline which was integrated to the LNA circuitry. The patch dimensions are first computed using the design procedures for a rectangular patch outlined in Antenna Theory [3]. The dimensions obtained were later input and simulated using Microwave Office as this software was able to consider two different dielectrics in its routine. The geometry of the CPPA is as given in Fig 1.

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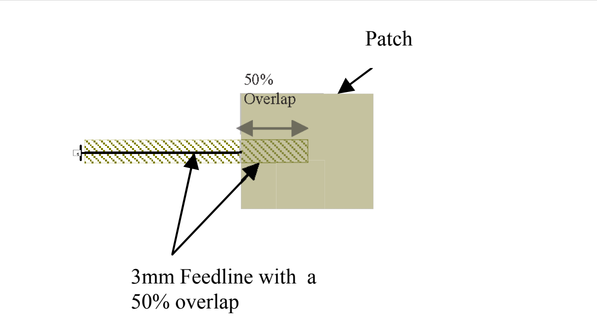

Figure 1: Geometry of the proximity coupled antenna with a 50% overlap.

The patch dimensions were modified through an iterative process to get the patch resonating at 5 GHz. The desired 5 GHz frequency was achieved for a patch dimension of L = 15.9 mm and W= 16 mm. The width of the feedline was standardized to 3 mm for both outside the patch and overlap. The inset overlap was maintained at 50% as the best return loss was obtained at this overlap [4].

2.2 Low Noise Amplifier Design

The low noise amplifier (LNA) was designed as a single stage amplifier to be integrated directly to the CPPA. As such it was designed on the same substrate as the feed line i.e the FR4 substrate, to directly integrate the feedline to the LNA as well as avail the design of the advantages of using a thinner substrate for the LNA circuitry [2]. After reviewing and testing the stability factors for unconditional stability using the S-Parameter Synthesis software by Michael Ellis, Agilent's e-pHEMT transistor ATF-55143 was selected for the LNA design. The unconditional stability, low NF and higher gain available for this transistor when biased at a V_{ds} = 3V and I_{ds} = 30mA made it a better choice for the design. Moreover, the ATF-55143 had an added advantage that it requires no negative power supply voltage [5].

As NF is the main consideration in this design, trade-offs need to be made to ensure a balance between the best possible gain, return loss, VSWR and good noise figure. This can be done by using constant gain circles and circles of constant noise figures to select a usable trade-off between gain and NF.

LINC2 was first used to automate the design of an LNA for a NF of 0.9 dB with a -10.5 dB input and output return loss. The design was then exported to MWO environment and further optimized and simulated. The simulation results for NF and gain were above expectation but the return loss was below the desired -12 dB or above. Further optimization was done after the DC and RF biasing to improve the return loss.

Biasing for the LNA circuitry is required for two purposes, namely first to keep DC from flowing into the AC portion (RF portion) of the design and secondly, isolating the RF from the power supply lines. The first aspect was achieved through DC blocks using chip capacitors, resistors, quarter-wave length radial stubs and quarter-wave high impedance transmission lines.

Isolation of RF from the power lines and also lower frequencies was done using 1000 pF chip capacitors. As a "rule of thumb" minimum reactance for good isolation should be 10 times the impedance of the circuit to which the bias feed is attached to. For this design the bias feed connects the circuit at a place where the impedance is roughly 50 Ω, hence the reactance for good isolation should be about 500 Ω. This was achieved using 50 Ω resistors.

2.3 Active Integrated Antenna with LNA

The integration of the CPPA and LNA is done by integrating or coupling the 5 GHz patch antenna to the LNA circuitry with the feed line to give the integrated device or ALNA. Figure 2 shows the coupled ALNA.

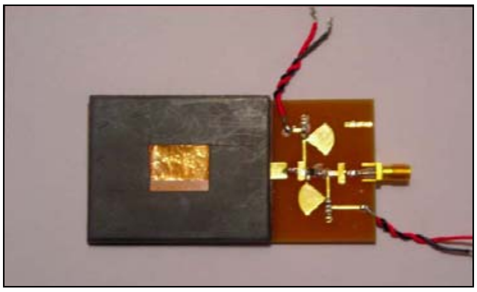

Figure 2: Active integrated antenna with low noise amplifier (ALNA)

3. Result and Discussion

3.1 Antenna Result

A return loss of -9.209 dB was obtained at a feed point impedance of 24.27 Ω in simulation. On matching the feed point to 50 Ω using the series tuning stub, the simulated return loss improved to -31.25 dB.

Four units of the designed patch were fabricated and tested. The results obtained on a Marconi Network Analyzer are as tabulated in Table 1.

Table 1: Simulated versus measured results of the patch at 5 Ghz.

	Patch Antenna	S_{11} (dB)	Bandwidth (GHz)	% Bandwidth	VSWR	%Power Reflected
	Simulated	-31.25	4.57-5.37	16.0	1.05:1	<0.1
Measured	Patch 1	-13.17	4.61-5.12	10.2	1.56:1	<10.0
	Patch 2	-15.9	4.62-5.24	12.4	1.38:1	<3.16
	Patch 3	-16.2	4.75-5.34	11.8	1.37:1	<3.0
	Patch 4	-17.4	4.60-5.27	13.4	1.31:1	<3.0

The best S_{11} reading obtained was around -17.4 dB at 5 GHz which translates into almost less than -0.08 dB Insertion Loss (or Mismatch Loss) and less than 3.16 % Power Reflection. The variations in the S_{11} readings of the 4 patches were due to etching defects, and also difficulty of aligning the patch to the feedline to obtain the best return loss. Patch 4 when tested on a HP Network Analyzer and successfully aligned with end of inset overlap right underneath centre of patch [4] it demonstrated a return loss of – 35.41 dB and a bandwidth of 16.4 % at 5 GHz.

The plot of the radiation patterns for the passive CPPA which are directional are as shown in Figure 3 and Figure 4. The radiation patterns show a good isolation of approximately 20-25 dBm between the co and cross polarization in both the E and H planes. The HPBW is about 105° in both planes and is wider than the simulated result of 80°.

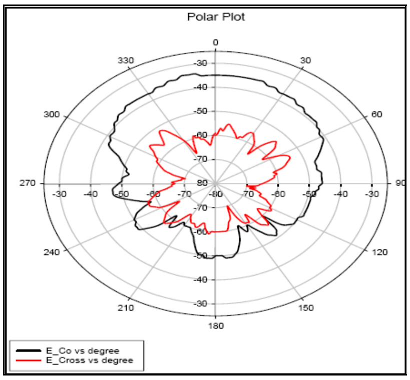

Figure 3: Radiation pattern - Co and Cross polarization vertical plot of the passive CPPA

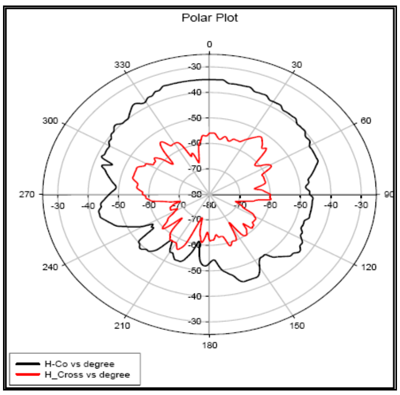

Figure 4: Radiation pattern- Co and Cross polarization horizontal plot of the passive CPPA

3.2 Low Noise Amplifier Result

The 50 Ω resistors as mentioned earlier, helped achieve a reactance of 500 Ω at both the bias feedlines. The bias Smith chart (Figure 5) below shows nearly 500 Ω of reactance from 4.5 to 5.5 GHz which is sufficient reactance for the isolation of the bias supplies.

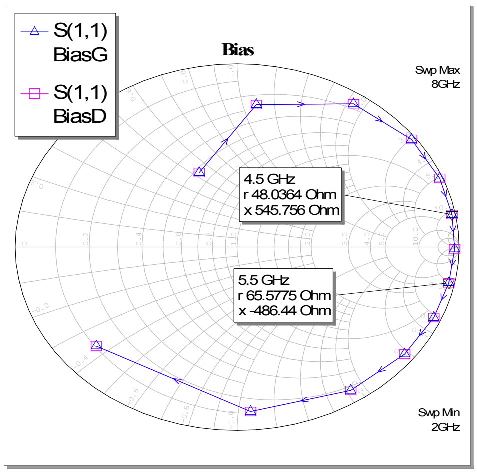

Figure 5: Bias Smith chart

Stability check for the final LNA circuit, however, showed that the circuit had become unstable and started to oscillate. This could be due to external feedback and excess gain outside the band of operation. The Rollet Stability Factor (K-Factor) started to dip below 1 from 4.9 GHz to around 6.7 GHz.

A topology with a source inductance for series feedback [6] but with an additional resistive loading was chosen to improve the stability. This is because although the source inductance improved the noise figure, the stability did not. The source inductance here was achieved by way of a short microstrip line between the source leads and the vias and not through a source inductor. By trial and error, a 6 Ω resistor was selected and this resistor provided unconditional stability throughout the operating band and a good way above and below the 5 GHz operating frequency. Figure 6 shows the simulation results after insertion of source inductance. The NF improved from 1.102 dB to 1.098 dB but the gain dropped by 0.19 dB and the input return loss deteriorated slightly by 0.82 dB. However, the output return loss improved by -10.38 dB.

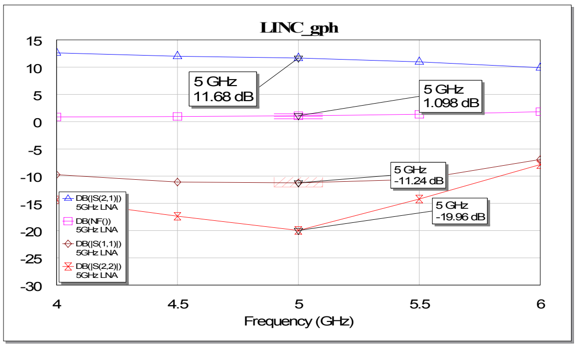

Figure 6: Final LNA after insertion of source inductance

Figure 7 shows the final LNA unconditionally stable after insertion of the 6 Ω resistor. The stability factor, K 1 and B1 are shown to be above 1 and 0 respectively throughout the frequency range from 2 GHz to 8 GHz thus satisfying the conditions for unconditional stability.

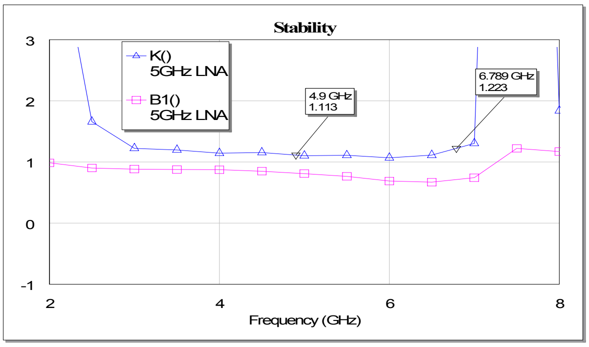

Figure 7: Final LNA unconditionally stable with 6 Ω stability resistor

The fabricated LNA was tested at Avago Penang's facilities and the results are as tabulated in Table 2.

Table 2: S-parameter and noise figure measurement of the LNA.

	Low Noise Amplifier	S_{11} (dB)	Gain S_{21}(dB)	S_{22} (dB)	S_{12} (dB)	Noise Figure (dB)
	Simulated	-11.25	11.67	-19.63	-17.19	1.09
Measured	Prototype Before Tweak	-5.95	7.05	-3.57	-21.29	1.45
	Prototype After Tweak	-6.78	8.12	-4.0	-20.5	1.37
	Avago's 5 GHz LNA	-15.26	11.53	-13.16	-17.57	1.97

The initial results were not too promising. Better results were obtained after tweaking the input and output matching network stub lengths of the LNA. The tweaking was done by using strips of copper foil to vary the length of the stubs until desired results were obtained. The tweaking approach is done to move Γ_{in} close to Γ_{opt} to obtain the best match noise.

Avago's 5 GHz LNA was also tested for comparison. The NF obtained was 1.97 dB compared to the NF of the tweaked prototype which was at 1.37 dB. Their LNA's NF should have been 1.2 dB as per Avago's Application Note: 1285. The high reading could have been due to soldering defects. The NF of the prototype should be around 1.22 dB after discounting 0.15 dB noise figure contribution from the connectors. The LNA's S_{11} was 4.47 dB lower than the simulated S_{11} of -11.25 dB and the gain was 3.55 dB lower than the simulated gain of 11.67 dB. One reason for the poor performance of the LNA could be because the LNA was fabricated from the integrated LNA portion of the ALNA. The LNA's input and output matching had been optimized to give the best return loss for the ALNA. As such by dissecting the LNA portion of the board from the ALNA and using it as a discrete LNA may not give the desired results. The LNA may have performed better had it been separately designed, optimized and fabricated. One consolation is that the noise figure of 1.22 dB obtained for the LNA after deduction of 0.15 dB for the connector losses, is close to that of the desired noise figure goal for the ALNA; lower the noise figure of the LNA the better would be the expected noise figure performance of the ALNA.

3.3 Active Integrated Antenna

The simulation results are shown in Figure 8 and Figure 9. The results indicate that the ALNA's NF is dependent on the performance of the LNA. This can be seen by the simulated results of the LNA without the CPPA being integrated in Figure 9. This is justified by the fact that the noise figure would not be the same if the LNA is connected to the CPPA using a 50 Ω connector [1] which is the aim of this research i.e to integrate the CPPA to the LNA to reduce the noise figure. The overall return loss and VSWR of the ALNA in simulation are -19.61 dB and 1.234 respectively.

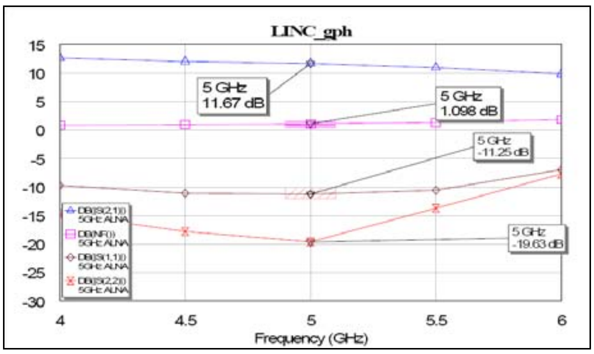

Figure 8: The simulated results of the ALNA

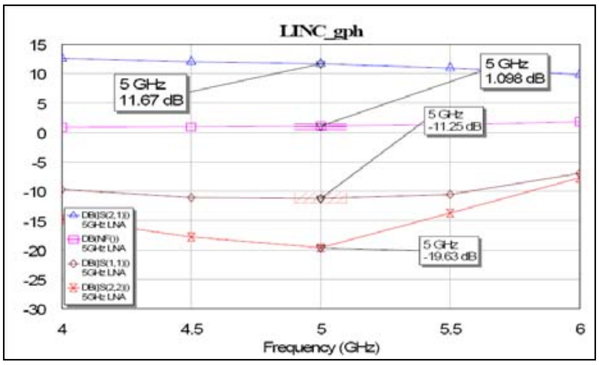

Figure 9: Simulated results of the LNA without CPPA

The return loss of the fabricated ALNA before tweaking was not so good; it registered a S_{11} of -6.3 dB with a VSWR of 3. Better results were obtained after tweaking at both the input and output matching circuits of the LNA portion of the ALNA. The output matching stub especially, was lengthened by soldering a rectangular strip of copper foil to extend it by a length of 10 mm and tweaked by slowly cutting it down to a length of 9.4 mm. The S_{11} peak of -18 dB at 4.7 GHz gradually moved towards the 5 GHz frequency point to register a value of about -12.75 dB.

The CPPA was also connected using a 50 Ω SMA plug to plug connector to Avago's 5 GHz LNA board and tested. The return loss obtained was summarized and tabled together with the results for the S_{11} obtained for the ALNA prototype before and after tweaking in Table 3.

Table 3: S-parameter measurement of the ALNA

LNAA	S_{11} (dB)	VSWR	%Power Reflected
Simulated	-19.61	1.23	1.00
Prototype before tweaking	-6.3	3.0	25.12
Prototype after tweaking	-12.7	1.6	5.33
Patch Connected to Avago's LNA	-12.05	1.67	10.00

4. Conclusion

The use of a two-layered substrate design with different dielectrics for the close proximity antenna had greatly improved the performance of the antenna. As for the LNA, it has been demonstrated that a modified design approach incorporating both stability resistor and inductive feedback can help to achieve unconditional stability. Fabrication and soldering proficiency to some extent affect the outcome of the actual performance of the ALNA. The aim of this research was to design an ALNA for WLAN applications at 5 GHz with a NF lesser than 1.2 dB, a return loss greater than -12 dB, a bandwidth greater than 10 %, and a gain greater than 10 dB. The measured results were a gain of 8.12 dB and a noise figure of 1.22 dB for the LNA after excluding losses 0.15 dB for the connectors, a return loss of -12.75 dB and a bandwidth of 10 % for the ALNA. Although the actual gain and noise figure of the ALNA were not measurable, going by the results obtained in Table 2 for the gain and NF of the LNA after tweaking, the gain for the ALNA is expected to be above 8 dB and close to the desired gain of 10 dB whilst the noise figure around 1.2 dB.

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