Design of High Gain, High Reverse Isolation and High Input Matched Narrowband LNA for GPS L1 Band Applications Using 0.18µm Technology

S. Juneja* and R. Sharma**(C.A.)

Abstract: Design of Global Positioning System (GPS) receiver with a low noise amplifier (LNA) in the front end remains a major design requirement for the success of modern day navigation and communication system. Any LNA is expected to meet the requirements like its ability to add the least amount of noise while providing sufficient gain, perfect input and output matching, and high linearity. However, most of the reported designs of LNAs present the need for striking a trade-off between these design parameters in order to obtain the desired performance for a particular RF receiver. This paper presents high gain (21dB), high input matched (-29dB), high reverse isolation (-41dB) and low noise figure (< 2dB) narrowband LNA for extremely low power level GPS L1 band signals broadcasting at 1.57GHz with a channel bandwidth of 10MHz. Inductive source degeneration topology is employed for the design and all the matching inductors in the circuit are used with fixed quality factor (Q) to model the losses for better tuning and matching. The design is carried out on Cadence Virtuoso Tool version IC6.1.6 and Spectre version MMSIM13.1 at 0.18µm technology node using a generic process development kit. Detailed mathematical analysis of the design is done and all the DC parameters like values of transconductance, gate source capacitance, drain source voltage, drain current, etc. are reported. Graphical analysis using Smith chart is carried out to present the results and to bring forth the trade-offs involved in the design. LNA draws 5mA current from 1.2V supply voltage and offers good linearity that is sufficient for GPS application and is measured by input intercept point 3 (IIP3 < -4dBm).

Keywords: Low Noise Amplifier, LNA for GPS Applications, Smith Chart Analysis of LNA, Matching Network for LNA, Inductive Source Degeneration, S-Parameters Analysis of LNA.

1 Introduction

There has been a persistent demand of a Low Noise Amplifier (LNA) capable of not only allowing the addition of least amount of noise in the received signal at the front end of RF receiver subsystem circuits but also provide a reasonable amount of gain with sufficient linearity [1]. Gain is required to amplify the received signal to a certain optimum level so that design restrictions on the subsequent stages of RF receiver including mixer, analogue to digital converter etc. as shown in Fig. 1 remain less stringent [2].

Similarly, linearity should be sufficiently high to ensure that intermodulation due to third and second order harmonic components don’t affect the operation of LNA [2].

Presence of LNA in the front end on the receiver side makes its design quite challenging because it needs to encounter distorted signals (caused by the interferences...
**Figure 1: RF Transceiver [2].**

**Table 1: Contemporary LNA designs.**

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Technique</th>
<th>Reference</th>
<th>Key Features and Performance Parameters</th>
</tr>
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</table>
| 1     | Folded cascode LNA | Kumaravel et al. [8] | - Folded cascode LNA with $g_m$ boosting has non linearity due to transconductance non linearity at low supply voltage.  
- It can be addressed using techniques like Derivative Superposition, Modified Derivate Superposition (MDS) [9].  
- LNA parameters reported in this design are $NF = 2.9\, \text{dB}$, Input return loss ($S_{11}$) $= -15\, \text{dB}$, Gain ($S_{21}$) $= 14.6\, \text{dB}$ and $IIP3 = 4.19\, \text{dBm}$ for 2.4GHz ISM band applications. |
| 2     | Inductorless LNA | Yu et al. [10] | - Inductorless LNA with parallel branches of common source and common gate path and a noise cancellation technique.  
- $NF = 3.8\, \text{dB}$, Power dissipation ($Pd$) $= 10.8\, \text{mW}$, $S_{11} = 14.5\, \text{dB}$ and $S_{11} = -7.8\, \text{dB}$ |
| 3     | LNA optimization using Smith chart | Nguyen et al. [11] | - It presents device optimization technique by graph based method using Smith chart to obtain trade-off between NF and $S_{11}$ for wide band LNA.  
- $NF = 4.6\, \text{dB}$, $S_{11} = -9.2\, \text{dB}$ and supply voltage $= 1.2\, \text{V}$ |
| 4     | ESD protected LNA | Leroux et al. [3] | - LNA for GPS L2 band (1.23GHz) using source degeneration with ESD protection.  
- $NF = 0.8\, \text{dB}$, $Pd = 9\, \text{mW}$ and $IIP3 = -11\, \text{dBm}$ |
| 5     | Cascode LNA | Rahman et al. [12] | - Inductive source degeneration cascode LNA for GPS L1 band (1.57GHz).  
- $NF = 1.157\, \text{dB}$, $S_{11} = 18.9\, \text{dB}$, $Pd = 11\, \text{mW}$ and supply voltage $= 1\, \text{V}$ |
| 6     | Interstage matching LNA | Manjula and Selvathi [13] | - Narrowband cascode LNA with interstage matching and shunt feedback for 2.4GHz applications.  
- $NF = 2.2\, \text{dB}$, $S_{11} = -11\, \text{dB}$, $S_{21} = 13\, \text{dB}$, $Pd = 1.5\, \text{mW}$ and supply voltage $= 1.5\, \text{V}$ |
| 7     | Inductorless CG LNA | Karimlou et al. [14] | - It discusses inductorless common gate (CG) LNA with shunt feedback technique to improve power consumption for wireless sensor networks applications.  
- $NF = 3.38\, \text{dB}$, $IIP3 = -4.32\, \text{dBm}$, $S_{11} = 18.2\, \text{dB}$ and $Pd < 1\, \text{mW}$ |
| 8     | Source degeneration LNA | Kundu R. et al. [15] | - LNA is proposed for ISM band using inductive source degeneration topology.  
- $NF = 2.34\, \text{dB}$, $S_{11} = -9.4\, \text{dB}$, $S_{21} = 31.53\, \text{dB}$, $Pd = 8.5\, \text{mW}$ |
| 9     | Body-biasing technique | Kumar et al. [16] | - LNA is designed for 5.5GHz and it claimed to improve linearity with $IIP3$ reported as $9.20\, \text{dBm}$ using body biasing technique but it dissipates $10.8\, \text{mW}$ power. |
| 10    | Body-biasing technique | Huang et al. [17] | - This technique is used to reduce power consumption in LNA at low operating voltages and ensures that gain transistors in LNA are in saturation region even for the low supply voltage.  
- But disadvantage with body biasing is that it requires an expensive triple well process. |
| 11    | Sub threshold LNA | Kumar et al. [18] | - In this LNA gain transistors are made to work in sub threshold region instead of strong inversion.  
- Sub threshold design has higher non linearity, smaller ratio of $g_m$ over $I_v$ (both are undesirable for LNA) |
| 12    | LNA-Mixer integration | Raja R. et al. [19] | - RF receiver front end that is an integration of LNA and mixer.  
- This design has high $NF = 9.5\, \text{dB}$. |
| 13    | Multi-Gain LNA | Qadir et al. [20] | - Multi-gain LNA using cascode technique for 2.4GHz wireless applications.  
- Gain $= 25/20/10\, \text{dB}$, $NF = 2.6 - 7\, \text{dB}$, supply voltage $= 1.5\, \text{V}$ |

from buildings, trees etc. (in the physical environment) with extremely small power levels up to -130dBm (typical example of a GPS signal) [3]. CMOS design process in modern day Integrated Circuit (IC) technology further makes the design of LNA more tedious due to reasons like addition of excess thermal noise because of presence of hot electrons in high electric fields, low transconductance and restriction in
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voltage headroom due to scaling of CMOS devices and integration of millions of transistors on a single SoC [1, 4-8]. These design process restrictions lead to higher noise floor and affects gain and linearity of LNA as well.

There have been efforts to overcome LNA design challenges [1, 3, 8-21] using techniques like folded cascode design, gain boosting techniques [8], derivative superposition [9], inductive source degeneration with ESD protection [3], interstage matching [13], inductorless design [14] etc. Table 1 provides a good summary of some of the notable work in this direction while clearly bringing forth the details of the techniques used for the purpose and results obtained.

Among all the LNA design techniques brought forward in table 1, it can be inferred that circuits (mentioned at sr. no. 1, 4, 5, 6 and 8) broadly based on inductive source degeneration topology have been found to be able to provide high gain and high reverse isolation for narrowband applications. Taking a clue from there, we in this paper report our results related to design of narrowband inductive source degeneration LNA capable of handling low power level signals specifically for GPS L1 band broadcasting at 1.57GHz with channel bandwidth of 10MHz.

Proposed LNA is simulated on Cadence Virtuoso Tool version IC6.1.6 and Spectre version MMSIM13.1 with 0.18µm technology node using generic process development kit. For source degeneration, input matching and output matching lossy inductors instead of pure inductors are used. A conscious effort has been made to improve upon the gain of the circuit by incorporating a large transistor in order to obtain higher $g_m/I_D$ ratio [6]. However, large transistors are known to suffer from losses due to higher gate resistance as well as higher parasitic capacitances [22], which affect reverse isolation of the circuit. This problem was addressed by incorporating multiple gate fingers of narrow width in the transistor (responsible for providing gain) in present work. The total width of the transistor in the proposed design is 500µm and is implemented using 10 gate fingers with width of 50µm each. A better trade-off between $NF (< 2\text{dB})$ and input return loss ($S_{11} = -29\text{dB}$) is achieved using the proposed LNA topology.

This paper has been divided in four different sections. Present section of introduction is followed by Section 2 which presents complete methodology with detailed mathematical analysis of proposed LNA that remains critical so as to calculate values of components used in the circuit design. Section 3 presents small signal s-parameters analysis, large signal analysis, Smith chart analysis along with trade-offs among different parameters of the proposed LNA under results and discussion section. Section 4 presents the conclusion of the work carried out in this paper.

2 Methodology

LNA circuit as shown in Fig. 2, which happens to be the variation of a standard inductive source degeneration topology, has been designed to obtain the value of gain in the range of 18-22dB and $NF$ close to 2dB. It must be noted that in most circuit simulations of LNAs presented in literature, ideal inductors are considered for matching and for source degeneration. However, in the proposed design, practical lossy inductors are modelled [23] with value of quality factor $(Q)$ equal to 5. Value of $Q$ has been chosen on the basis of earlier reported work by Shaeffer and Lee [1].
Design of High Gain, High Reverse Isolation and High Input Power Supply Variations or Noise. 

GPS signal occupies a narrowband (10MHz) over high frequency carrier. In order to obtain these kind of values of desired selectivity in narrowband LNA, quality factor is chosen between 4 and 5 [1]. Mathematically $Q$ is given by Eq. (4), where $\omega$ is frequency of operation.

$$Q = \frac{1}{Z_{in} \omega C_{gs}}$$  

Transistor M2 forms a current mirror with transistor M1 and is responsible for setting required drain current ($I_D$) in M1 for desired $g_{m}I_D$ ratio and for adequate forward gain. Drain current ($I$) is set in M2 by using appropriate size of M2 and current limiting resistor $R_1$ as shown in Fig. 2. $I_D$ in M1 is obtained from Eq. (5). Resistor $R_2$ provides high impedance connection between M2 and M1.

$$\frac{W}{L} = \frac{I_D}{I}$$  

Table 2 shows the values of crucial DC parameters obtained for the proposed LNA circuit using analog simulation in Cadence Virtuoso tool. Theoretical values of $g_m$ and $C_{gs}$ as obtained from Eqs. (2) and (3), respectively, are very close to their simulation values listed in Table 2. This indicates that adequate $g_{m}I_D$ is available in the circuit to have desired gain and parasitic capacitances ($C_{bd}$ and $C_{sd}$) are extremely small.

Theoretical values of $L_4$ and $L_5$ differ from their practical values in the design. This is due to the fact that in theoretical analysis only $C_{ox}$ of MOSFET is considered and $C_{sd}$ and $C_{bd}$, that are small values in comparison to $C_{gs}$, are ignored. Also theoretical values of components are calculated considering the perfect match condition (i.e. impedance of RF source and load is equal to 50Ohms). Implementation of the design on Cadence Virtuoso tool was started with theoretical

### Table 2 DC parameters.

<table>
<thead>
<tr>
<th>Parameter [unit]</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transconductance ($g_m$) [mA/V]</td>
<td>85</td>
<td>9.13</td>
<td>85</td>
</tr>
<tr>
<td>Drain Current ($I_D$) [mA]</td>
<td>5</td>
<td>0.5</td>
<td>5</td>
</tr>
<tr>
<td>Drain Source Voltage ($V_{ds}$) [Volts]</td>
<td>0.637</td>
<td>0.6</td>
<td>0.56</td>
</tr>
<tr>
<td>Gate Source Voltage ($V_{gs}$) [Volts]</td>
<td>0.6</td>
<td>0.6</td>
<td>0.562</td>
</tr>
<tr>
<td>Gate Capacitance ($C_{gd}$) [pF]</td>
<td>524</td>
<td>-</td>
<td>524</td>
</tr>
<tr>
<td>Threshold Voltage ($V_T$) [Volts]</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Gate Oxide Capacitance ($C_{ox}$) [F/m²]</td>
<td>8.46x10⁻⁴</td>
<td>8.46x10⁻⁴</td>
<td>8.46x10⁻⁴</td>
</tr>
<tr>
<td>Mobility of Charge Carriers ($\mu_n$) [cm²/V·sec]</td>
<td>327.37</td>
<td>327.37</td>
<td>327.37</td>
</tr>
</tbody>
</table>

Additional capacitors have been added in the circuit so as to ensure good quality matching at both input and output ports and to provide better isolation to the complete circuit from power supply noise. Role of all the circuit elements have been discussed in detail in this section.

M1 is a common source NMOS transistor that is inductively degenerated and is responsible for not only providing gain in the circuit but also keeping a check on the noise performance of the circuit. Gate source capacitance ($C_{gs}$) of M1 forms an input matching network with inductors $L_g$ and $L_s$. Lossy inductors have been used so as to achieve more realistic results. Circuit has been fed by RF source with 50 Ohms termination and signal power level of -40dBm at operating frequency of 1.57 GHz. Circuit components values like inductors $-L_3$ and $L_s$, and W/L ratio of gain transistor M1 are calculated using Eqs. (1)–(3) so as to obtain mandatory 50 Ohms termination [24].

$$Z_m = \frac{L_g g_m}{C_{gs}}$$  

where, $g_m$ is transconductance of M1 and is given by Eq. (2) and $C_{gs}$ of M1 is given by Eq. (3):

$$g_m = \sqrt{2\mu_n C_{ox} \frac{W}{L}}$$  

$$C_{gs} = \frac{2}{3} W L C_{ox}$$  

$I_D$ is drain current in M1, $C_{ox}$ is oxide capacitance per unit area and $\mu_n$ is mobility of charge carriers [6]. In order to have high forward gain in LNA high $g_{m}I_D$ ratio is desired [1].

Circuit exhibits further advantage in terms of reduction of effect of $C_{ob}$, better gain, better stability and high linearity owing to usage of a cascode stage between M1 and M3. A dedicated effort has been made to propose a design of the circuit which helps in saving the chip area owing to selection of same size of M1 and M3 [25] and common usage of drain area of M1 with source area of M3.

$L_g$ forms a parallel tank circuit with total capacitance at the output node ($C_{gd}$, $C_{bd}$ - gate-drain and drain-body capacitance respectively) in addition to the capacitance of the subsequent stage, assuming that there is a down converter mixer stage which would be used in addition after LNA circuit in a real life application. An additional capacitor $C_g$ is added in the circuit for better tuning of the tank circuit. Similar explanation of this part of the circuit has been provided earlier by [1, 5, 7]. Other circuit components in Fig. 2 are coupling capacitors (C1 and C4) whose values are swept and optimized to achieve close to perfect matching at input and output ports. Capacitors C2 and C3 are used to suppress any power supply variations or noise. GPS signal occupies a
values of inductors $L_g$ and $L_s$. Their values were swept in the design to get desired small signal s-parameters first and then large signal linearity parameters.

3 Results and Discussion

Having explained the design part of LNA circuit under consideration in the Methodology section, present section of Results and Discussions summarizes all the obtained results and discuss the same in light of already reported work. Simulations of the proposed LNA circuit are carried out using Spectre simulator version MMSIM13.1 [26].

3.1 Small Signal S-Parameters Analysis

S-parameter analysis is carried out to linearize the circuit about DC operating point by applying a small test signal with the power level of -40dBm at 1.57GHz. Fig. 3 shows the plot for $S_{11}$ and $S_{12}$ against variation of frequency from 500MHz to 3GHz. It can be clearly observed that a dip in the values of $S_{11}$ and $S_{22}$ in the plot is observed in a narrow band at the frequency of interest, i.e. 1.57GHz. Although the values of both $S_{11}$ and $S_{22}$ are found to be below 0dB for a broader range of frequency, the same fall to -29dB and -10.72dB respectively over the operating frequency of 1.57GHz. This clearly indicates that we have been able to establish good matching at both the input and output ports.

Performance of LNA circuit is further verified by finding out the results for forward gain ($S_{21}$) and reverse isolation ($S_{12}$) as shown in Fig. 4. While $S_{21}$ is constant for a range of frequencies, the peak value of 21dB is found at 1.57GHz. Similarly $S_{12}$ which is indicative of leakage power from output to input is constant over a range of frequencies but is observed to possess the lowest value equal to -41dB at frequency under consideration. It indicates very small leakage power from output back to input at operating frequency. High gain and good reverse isolation is due to good input and output matching in the circuit.

Another important parameter, which must be taken into consideration for design of LNA is noise figure (NF). Accurate estimation of the same becomes even more important as NF of LNA gets added directly to the total NF of the RF receiver [5]. Fig. 5 depicts a measure of NF over a broader range of frequency from about 0.5GHz to about 3GHz. As can be clearly seen that NF is observed to be almost constant from 500MHz to 1.57GHz and then rises sharply, NF of 1.98dB is obtained at 1.57GHz in the proposed design. Some of the earlier published works [8, 10, 13-16, 20] have also reported NF in the range of about 2 to 3dB for the LNAs using inductive source degeneration topology. Noise in the LNA circuit exist due to losses caused by gate resistance and due to parasitic capacitances primarily dominated by $C_{gs}$, $C_{gd}$, and $C_{db}$ of the main transistor (responsible for gain) in the circuit. In the proposed design effect of gate resistance is mitigated by using narrow gate fingers and effect of parasitic capacitances is addressed with optimum matching using inductors at input and output ports. Cascode configuration in the circuit also plays a vital role in removing Miller effect caused by $C_{gd}$ in the circuit.

We have also calculated the theoretical value of NF using Eqs. (6) and (7) [1].
The delta test is performed. Results of the same

delta test of the

is < 2dB and

is less than 1

r than zero but is an extremely small value. Closeness of GUMAX and GMAX as shown in Fig. 8, plot of GUMAX and GMAX asserts that $S_{12}$ of the

propose LNA is extremely small.

3.2 Graphical Analysis Using Smith Chart

Graphical analysis of LNA S-parameters using Smith chart is done to understand the trade-offs between design parameters and to optimize them. References [11] and [27] have used Smith chart method for optimization of LNA. Both $G_A$ and $NF$ of LNA are function of source reflection coefficient ($\Gamma_s$) [24], therefore available gain circle (GAC) and noise circle (NC) is plotted on Smith chart of $\Gamma_s$. Fig. 9(a) is a plot of GACs (co-centric circles) for different values of gain at frequency of interest. Circle with the smallest radius (blue circle) corresponds to maximum gain which is 21dB for the proposed design. Center of this circle corresponds to value of $\Gamma_s$. Ideally center of GAC should lie at the center of smith chart (where $\Gamma_s = 0$), practically it should be close to the center of smith chart and is equal to $S_{11}^\ast$ (conjugate match i.e. $\Gamma_s = S_{11}^\ast$). As can be seen from the plot in Fig. 9(a) center of GAC lies very close to center of smith chart which is an indication of near perfect input match. Similarly, Fig. 9(b) is plot of NCs for different values of $NF$. Circle with smallest radius (green color) corresponds to minimum $NF$ which is < 2dB and center of this circle corresponds to value of $\Gamma_s$ for most optimum $NF$. Fig. 10(a) is a plot of most optimum GAC (blue circle) and NC (green circle), their centers do not coincide which is indicative of a fact that there is a trade-off between Gain and $NF$. However for optimum design both centers should lie close to the center of Smith chart.

$S_{12}$ of LNA should be extremely small as it is obtained...
in the proposed design and should lie close to center of Smith cart. $S_{11}$ and $S_{22}$ should also lie close to center of Smith chart. Fig. 10 (b) is $S_{12}$, $S_{11}$, and $S_{22}$ plots on Smith Chart. $S_{12}$ is a purple color dot, which lies exactly at the center of Smith chart. $S_{11}$ traces orange color curve in the figure. It indicates value of $S_{11}$ at different frequencies. At 1.57GHz, $S_{11}$ is 0.018+j0.084 with normalized input impedance of LNA at this point equals 0.98+j0.16 (very close to the center of smith chart). Similarly $S_{22}$ traces blue color curve and at 1.57GHz, its value is 0.12+j0.249 with normalized output impedance equal to 1.11+j0.60.

3.3 Large Signal Analysis

Linearity of LNA is measured using large signal analysis that gives range of input signal power levels that could be amplified by LNA without causing intermodulation, compression, and blockage of adjacent channels. Linearity is measured using 1dB compression point and Input Intercept Point3 (IIP3). Fig. 11 is plot of 1dB compression point in the proposed LNA found to be equal to -18.6dBm which is quite sufficient for this design as GPS signal power is always below -40dBm. In the proposed LNA for GPS L1 band, channel bandwidth is 10MHz. Two adjacent channels $-\omega_1$ and $\omega_2$ produce 3rd order intermodulation components $2\omega_1\pm\omega_2$, $2\omega_2\pm\omega_1$ due to non-linearity of the circuit. IIP3 is a hypothetical point as shown in plot in Fig. 12 where 3rd order power gain line of intermodulation component intersects with fundamental frequency power gain line. IIP3 of proposed LNA is -4dBm and is a measure of linearity of LNA. Theoretically it should be at least 10dBm above 1dB compression point.

3.4 Comparative Analysis

Table 3 shows the comparison of LNA proposed in this paper with the ones already existing in the literature.

Comparison has been made with some of the very recent work published by Abdelhamid et al. [28], Qadir et al. [20], Yadav et al. [21], Kumar et al. [18], Yu et al. [10] and Safari et al. [29] respectively. While Abdelhamid et al. [28] have used a 65 nm technology node to design LNA circuit, Qadir et al. [20] and Yadav et al. [21] have used 130 nm and 90 nm technologies, respectively. Kumar et al. [18], Yu et al. [10] and Safari et al. [29] have used 180 nm technology node. Value of $S_{11}$ is reported to be -29dB in the present paper which is found to be the least among contemporary LNA designs. While Yadav et al. [21] have reported the highest value of gain of the order of 29.25dB using 90 nm technology node, but the power drawn is higher than the value reported in the present work. Further, the value of gain reported in this work is comparable to Abdelhamid et al. [28] that too with better values of noise figure. $S_{12}$ value reported by Abdelhamid et al. [28] stands out to be the best (-50dB). In the present work $S_{12}$ is reported as -41dB which is better than all the other designs compared in table 3. Value of power dissipation reported in this work equal to 6mW is also quite optimum and is comparable to the rest of the topologies. Overall, it is found that the circuit presented in this work is quite optimized to obtain a reasonably good combination of all the parameters viz. $S_{11}$, $S_{12}$, Gain, $Pd$, $NF$ and IIP3 in comparison to some of the latest works in this field. In addition, figure of merit (FoM) for all six LNA designs compared with the present work is calculated using Eq. (8) [30] and it has been found that FoM of present work is quite comparable with already existing designs.

$$FoM = \frac{Gain[abs]}{(NF[abs]-1)Pd[mW]}$$ (8)

Results obtained here may go a long way in giving further direction to design of next generation of LNA circuits for dedicated applications.

Development of dedicated models for various electronic components (both active and passive) and their usability in millimeter wave applications will be the subject matter of future course of research by us.

4 Conclusion

Narrowband LNA using inductive source degeneration topology is designed for GPS L1 band application broadcasting at 1.57GHz. Inductors with quality factor to model the losses are used for better tuning and matching in the design. Detailed analysis is carried out and all the DC parameters are reported. Smith chart analysis of results is presented that helped
in understanding the trade-offs and it also facilitates fast optimization. The proposed LNA is compared against several contemporary narrowband LNAs designed using same inductive source degeneration topology and on several parameters including $S_{11}$, $S_{12}$, Gain and NF.

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References


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