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Suppression of Microwave High-Speed Circuit Noise by Using a 10 GHz Transimpedance Amplifier at 30 ^{o}C

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ABSTRACT

A 10 GHz low noise transimpedance amplifier (TIA) is designed in which a new high-speed Angelov transistor model was employed. Thermal circuit components were simulated for noise measurement at 30ºC at which a typical microwave noise of 20 pA/√Hz was applied as the TIA input. A form of feedback topology helped to reduce the minimum noise figure to 3 dB, while the $|S_{21}|$ parameter gain proved to be 21.7 dB. A noise voltage at the TIA output was 3.23×10^{-15} V^2/Hz. The designed circuit showed a stability factor value of 0.36 which is considered as conditionally stable.

Keywords: Low noise amplifier, transimpedance amplifier, noise figure, Angelov transistor.

كبح ضوضاء دائرة مايكرويف عالية السرعة باستخدام مضخم الممانعة البينية عند التردد 10 GHz وبدرجة حرارة 30 درجة مئوية

الملخص

تم تصميم مكبر الممانعة البينية عند تردد 10 GHz باستخدام أنموذج ترانزستور انجيلوف فائق السرعة، إذ تمت نمذجة سلوك القطع الالكترونية عند درجة حرارة 30ºC وذلك بهدف قياس ضوضاء الدائرة. تم إدخال قيمة ضوضاء تعادل 20 pA/√Hz الى دخل الدائرة التي اشتملت على نظام تغذية استرجاع والذي ساعد في الحصول على 3 dB كأقل نسبة ضوضاء ممكنة وعامل ربح $|S_{21}|$ تم قياسه بقيمة 1.7 dB كذلك تم قياس قيمة فولتية الضوضاء عند خرج الدائرة فكانت بقيمة 3.23×10^{-15} V^2/Hz. أظهرت الدائرة الالكترونية المصممة عامل استقرار مقداره 0.36 وبذلك عدت مشروطة الاستقرار.

الكلمات الدالة: مكبر منخفض الضوضاء، مكبر الممانعة البينية، عامل الضوضاء، ترانزستور انجلوف.

INTRODUCTION

Low noise amplifiers (LNA) are one of the key components in receivers because it tends to dominate the sensitivity and noise figure (NF) of the whole system (Carrillo *et al.,* 2009). .

Generally, the main goal of LNA design is to achieve simultaneous noise and input matching (SNIM) at any given amount of power dissipation (Nguyen *et al.,* 2004).

Designing wideband LNAs for wireless applications presents two levels of challenges. In the first place, having fast and low noise transistors depends on the available technology. Traditionally, wideband microwave amplifiers relied on transistors realized with composite semiconductors, e.g., GaAs, because of the intrinsic superior frequency characteristics of such devices. Silicon technology, on the other hand, has been employed to design and fabricate amplifiers, even wideband ones, for particular applications, e.g., optical communications, that require different specifications compared to wireless systems. In wireless mobile communications systems, silicon integrated circuits have been widely employed in narrow-band systems, where limited gain and increased parasitics are tolerable due to lower operating frequencies and the application of tuned networks (Angelov *et al.,* 1996).

In this paper, a low noise amplifier was designed in a form of transimpedance configuration, in which thermal effects were taken into account. An optimized values for minimum noise figure, transimpedance amplifier gain and stability factor were obtained.

The concept of a transimpedance amplifier (TIA) as the forward system, requires that the feedback network sense the output voltage and return a current to the subtractor. A "voltage-current feedback" refers to the quantity sensed at the output, and a fractional quantity returned to the input. Such a feedback network must appear in parallel with the output and with the input, ideally providing both an infinite input impedance and an infinite output impedance
(Razavi, 2006).

In this work, a Microwave office 2009 development environment software was utilized to study the behavior of the proposed circuit. This software is capable of implementing electronic circuits at high-speed configuration. That is due to its advanced features of simulating high-speed transistor models with temperature effects taken into account.

S- parameter, Stability and Gain analysis

A network behavior at microwave frequencies can be characterized using the scattering parameter (S-parameter), these parameters are defined in terms of travelling waves, Fig. (1) shows the incident and reflected waves for two ports network.

The relationship between the S-parameter and the incident and reflected waves can be expressed as follows:

$$b_1 = s_{11} a_1 + s_{12} a_2$$
$$b_2 = s_{21} a_1 + s_{22} a_2 \quad \ldots\ldots\ldots..(1)$$

Where a_i and b_i are the incident and reflected waves respectively at port i .

The stability of an amplifier is very important consideration in a microwave circuit design. Stability or resistance to oscillation in a microwave circuit can be determined by the S-parameter. Oscillations are possible in a two-port network if either or both the input and the output port have negative resistance. This condition occurs when the magnitude of the input or output reflection coefficient is greater than one, $|\Gamma_{in}|\rangle 1 or |\Gamma_{out}|\rangle 1$ (Gonzalez, 1997).

There are two types of amplifier stability, unconditionally stable and conditionally stable. In the former, the real part of the input and output impedances of the amplifier is greater than zero for all passive load and source impedances, however, the amplifier is said to be conditionally stable if the real part of the input or output impedances of the amplifier is less than zero for at least a passive load or source impedances. The stability test should be done for every frequency in the desired range (Gonzalez, 1997).

In practice, most of the microwave transistor amplifiers are potentially unstable because of the internal feedback. A form of feedback from the common-gate HEMT Angelov output to the input of the common-gate HEMT Angelov transistor matrix is utilized to overcome the stability problem. The transfer function of the circuit in Fig. (2) with respect to output impedance is derived as in equation(2). Hence, the frequency response H(s) is evaluated in which s = jω: (Razavi, 2006).

$$H(s)=\frac{R_1R_2R_3\frac{L_1}{C_1}\frac{L_2}{C_2}\frac{L_3}{C_3}\frac{1}{C_4}s}{R_1R_2R_3L_1L_2L_3\left(\frac{C_1+C_2+C_3+C_4}{C_1C_2C_3C_4}\right)s^2+L_1L_2L_3\left(\frac{R_1R_2+R_2R_3+R_1R_3}{C_1C_2C_3C_4}\right)s+R_1R_2R_3\left(\frac{L_1L_3+L_2L_3+L_1L_2}{C_1C_2C_3C_4}\right)} \quad \ldots\ldots (2)$$

A range of input frequencies of (5-15 GHz) was applied as main signal. An ($|S_{21}|$) parameter showed a gain of (21.7 dB) at (10 GHz) with a bandwidth of (8.37 GHz) as in Fig. (3), in contrast, the ($|S_{11}|$) parameter indicates that there is a limited return loss as to the applied main signal, which is (-0.46 dB) at (10 GHz) as in Fig. (4). Solving for equation (2) in which $s = {-b \pm \sqrt{b^2-4ac}}\big/{2a}$ and hence $|s| = 41.6364 * 10^9$. Dividing by (2π), f = 6.63*10^9 = 6.63 GHz which is the first pole. Subtracting from (15GHz), we obtain a bandwidth BW=8.37GHz . As for the S-parameters, the values at (10GHz) were chosen.

Above analysis were performed with the existence of thermal sources at (30 ^oC) which included resistors and HEMT transistors models. However, when a (100 μA) input signal is applied into the circuit in Fig. (2), a voltage swing of (54 mV) was obtained. That means a transimpedance gain of (54.64 dBΩ). As far as the stability factor K is concerned, Fig. (5) indicates a value of 0.36 at 10GHz which suggests that this particular microwave circuit is conditionally stable for which the real part of Z (input impedance) is less than zero as in Fig. (6).

Noise Figure Analysis

The concept of noise figure of a network is defined as the signal-to-noise power ratio at the input to the signal-to –noise power ratio at the output

$$F = \frac{S_i/N_i}{S_o/N_o} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Thus the noise figure of a network is the decrease or degradation in the signal – to –noise ratio as the signal goes through the network, (Agilent, 2010).

An input-referred noise (IRN) of (20 pA/√Hz) is applied in which the mentioned amount of (IRN) is a typical value in low noise amplifier circuits, (Liu and Wang, 2004). Temperature rise, up to (30^{o}C) was taken into account regarding main thermal sources in the (TIA) amplifier in Fig. (2). Main thermal sources are the resistors and HEMT angelov transistors. A minimum noise figure of (0.36 dB) was obtained at (10 GHz) at above temperature before input-referred noise is applied as in Fig. (7). While the noise voltage at output was ($4.16*10^{-17}$ V^2/Hz) as in Fig. (8). Once a microwave noise signal is applied with the amount of (20 pA/√Hz), the minimum noise figure of around (3 dB) was achieved as in Fig. (9) with an output noise of ($3.23*10^{-15}$ V^2 /Hz)as in Fig. (10).

Comparison With Already Published Results

This work has been compared to already published results as in (Lu *et al.,* 2006), for which the amplifier bandwidth, minimum noise figure, $|S_{11}|$ and $|S_{21}|$ proved to be compatible despite of the fact that in this work, main thermal sources (i.e resistors and Angelov model transistors) were taken into account as temperature was set up to be 30ºC as in Table 1. In this work, the input bandwidth was improved by a Twin T Notch filter supported by the feedback topology of pi type inductive peaking at the common-gate transistor matrix in a form of transimpedance amplifier. In the published result, the use of a shunt base-emitter capacitor and weak shunt resistive feedback in a cascade amplifier with inductive degeneration using silicon-germanium (SiGe) heterojunction bipolar transistor (HBT) (Lu *et al.,* 2006)**.**

Table 1: Comparison with already published results (Lu *et al.,* 2006).

	BW (GHz)	Minimum NF (dB)	$\|S_{11}\|$ (dB)	Gain($\|S_{21}\|$) (dB)	Thermal Sources Temp. (ºC)
This work	8.37	3	-0.46	21.7	30
Lu	0.1-13.6	1.8	<-7.2	20.3	-

DISCUSSION

The presence of the twin T notch filter (high pass) at the input of TIA circuit in Fig.(2) represents an important step towards blocking any dc component which might shift the operating point of the Angelov common-source configured transistor.

This filter also considered as a current to voltage converter which is an initial step in a transimpedance amplifier. The common –source transistor matrix (first stage) enables the main signal to have a sufficient gain and bandwidth at the same time, although that there is no actual reduction in noise at this stage. However, once the amplified signal is applied at the source of the common –gate transistor matrix, it doesn't only get amplified (in phase), but also, there is a form of feedback that consists of another twin T notch filter as well as a pi type inductor peaking. The pi type inductor peaking feedback do actually resonate with Angelov model internal parastic capacitances, which is the main effect an TIA bandwidth extension. It also helps as a feedback in a common-gate setup on noise reduction in which unwanted harmonics are significantly blocked due the resonance case explained above. The minimum noise figure analysis do confirm this fact.

Incidentally, main thermal sources (i.e resistors and transistors) were set at 30°C (in simulation), it turns out that there was an actual gain in $|S_{21}|$ parameter nevertheless, with good stability factor. There was also a significant transimpedance gain reported.

The effect of having the operating temperature to be at 30 °C for the HEMT transistor model can be explained. To approach a real-time TIA circuit, the behavior of the circuit cannot be evaluated without the temperature influence. Further more, given the fact that this work involves a suppression of microwave noise, it is important to see whether or not that the 30 °C operating temperature could have had a dominating effect on the microwave noise, in this case, the microwave noise not only was detectable, but also it was possible to have it suppressed. This idea could have a very important application in which the thermal noise does not effect the detection or the suppression of microwave noise.

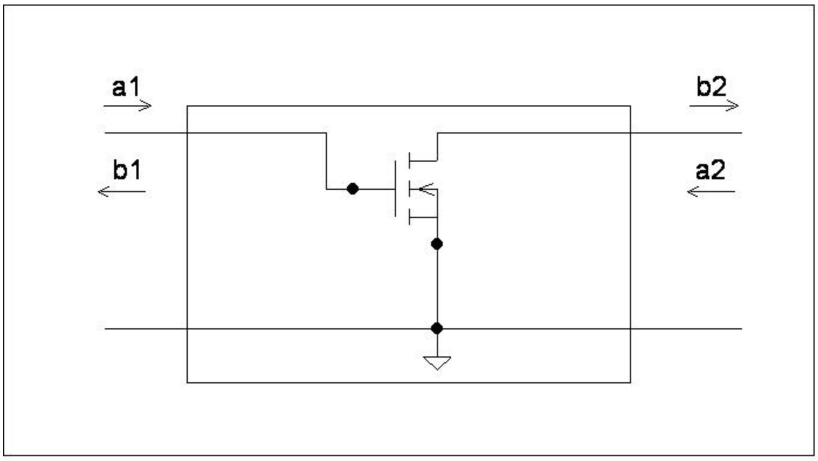

Fig.1: A transistor two port network.

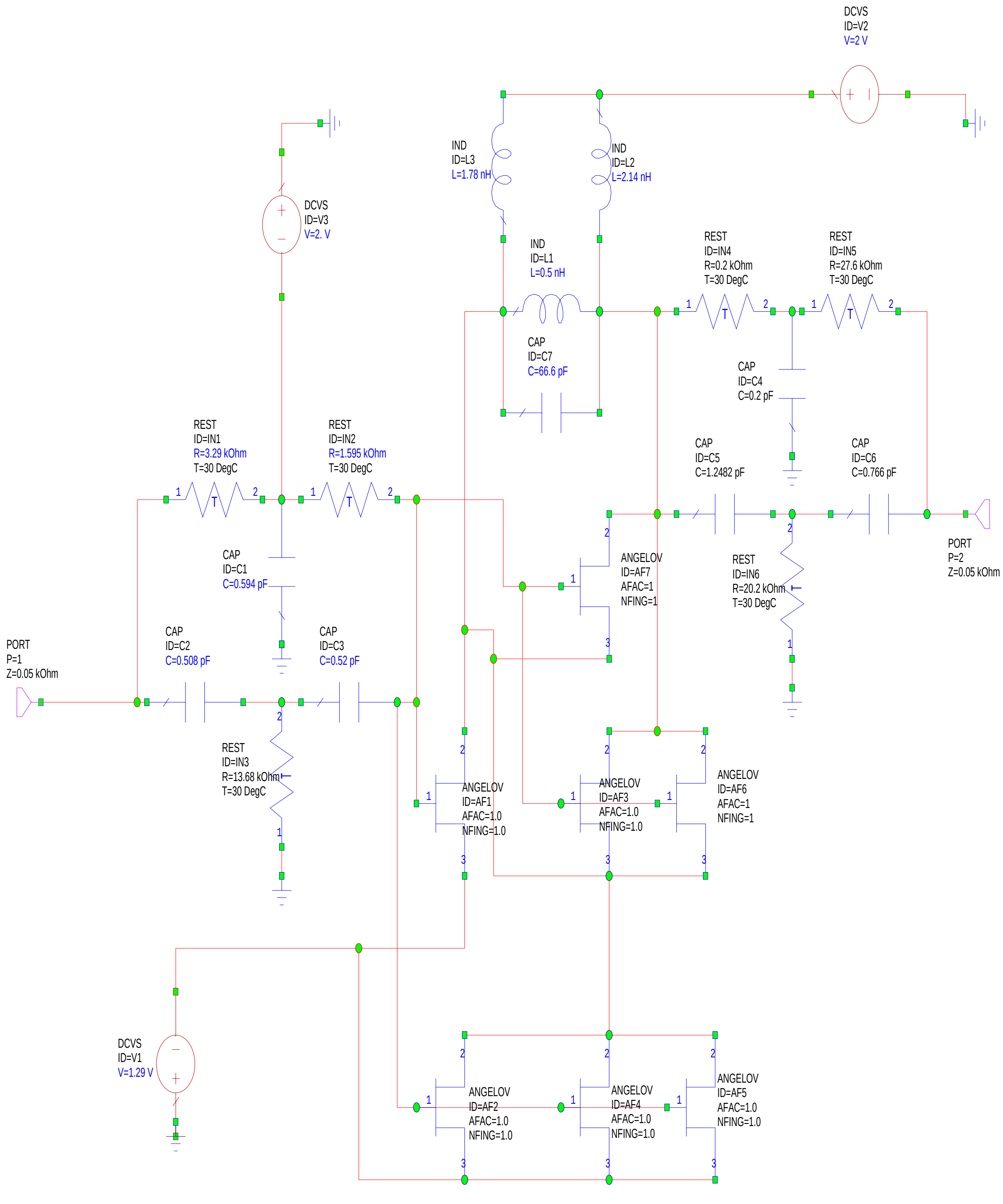

Fig. 2: Main TIA amplifier.

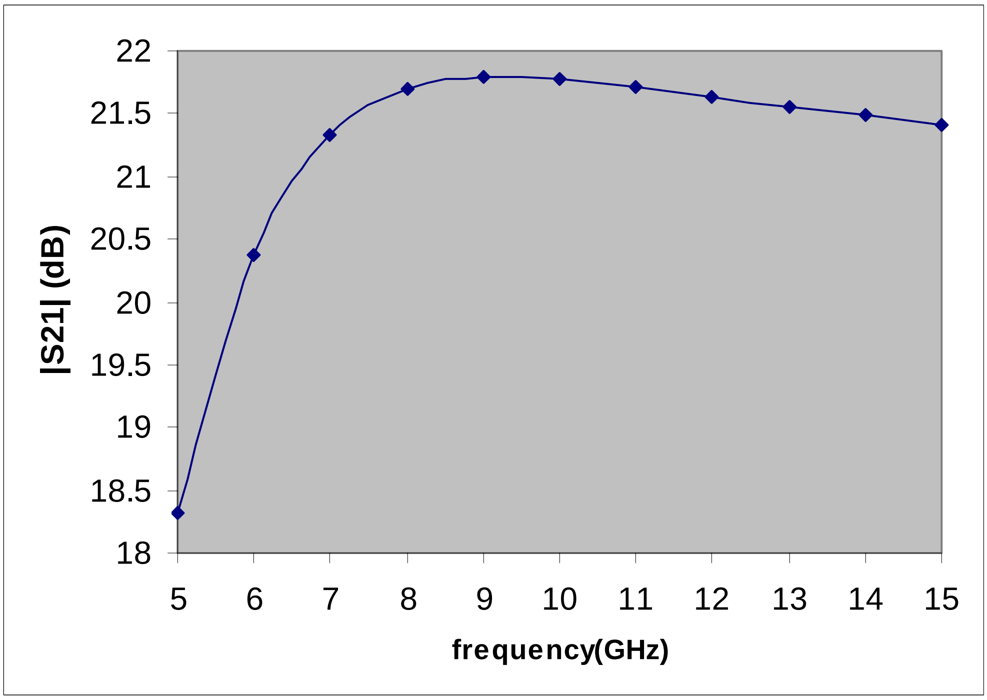

Fig. 3 : TIA gain versus frequency.

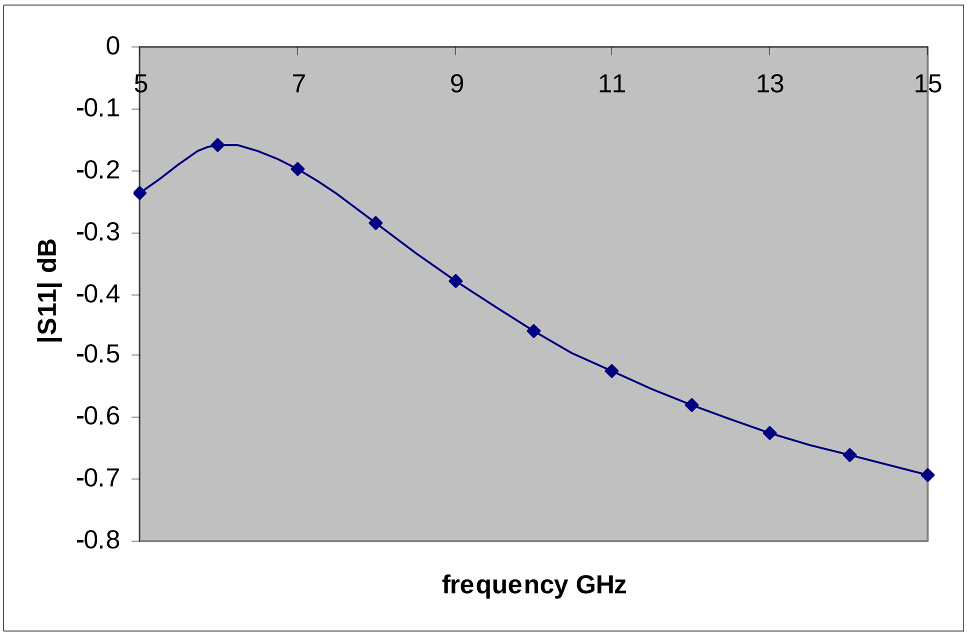

Fig. 4: Reflected signal from TIA input versus frequency.

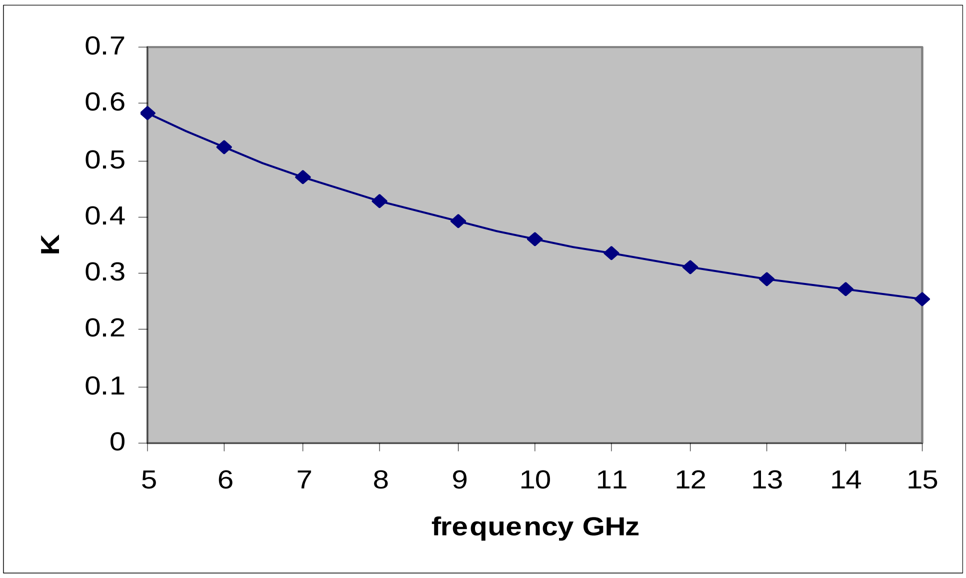

Fig. 5: TIA stability factor which indicated conditionally stable state at 10 GHz.

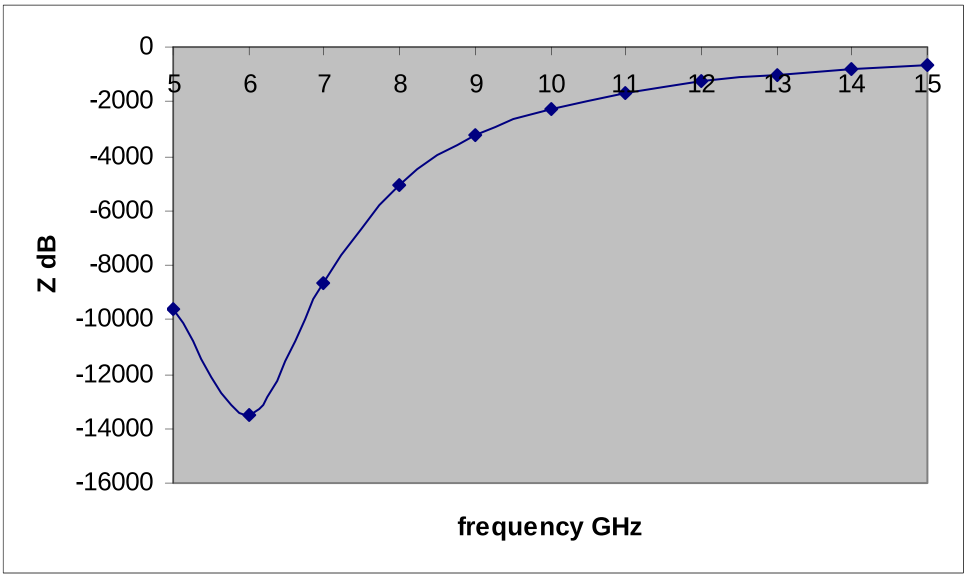

Fig. 6: TIA input impedance (real part) which confirm TIA circuit stability factor.

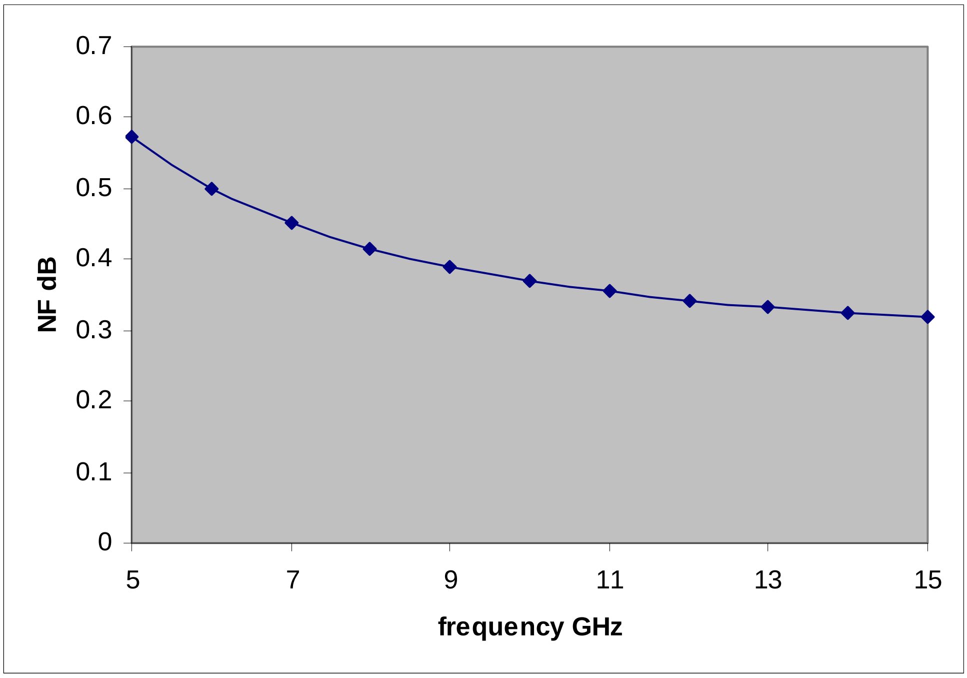

Fig. 7: Minimum noise figure before applying noise at TIA input.

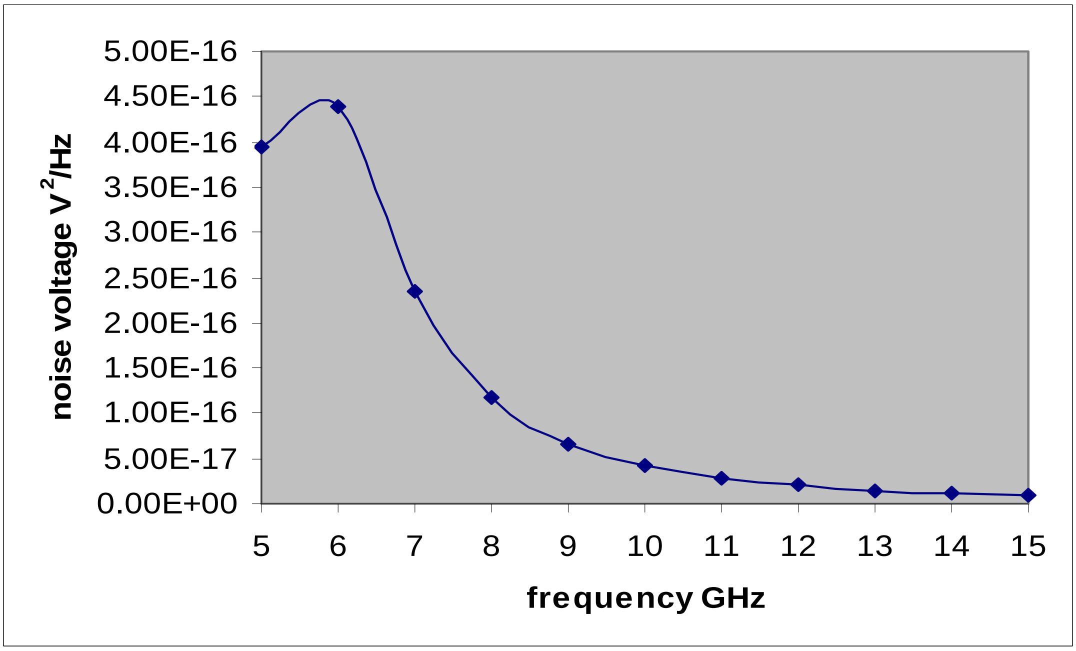

Fig. 8: Noise voltage before applying noise at TIA input.

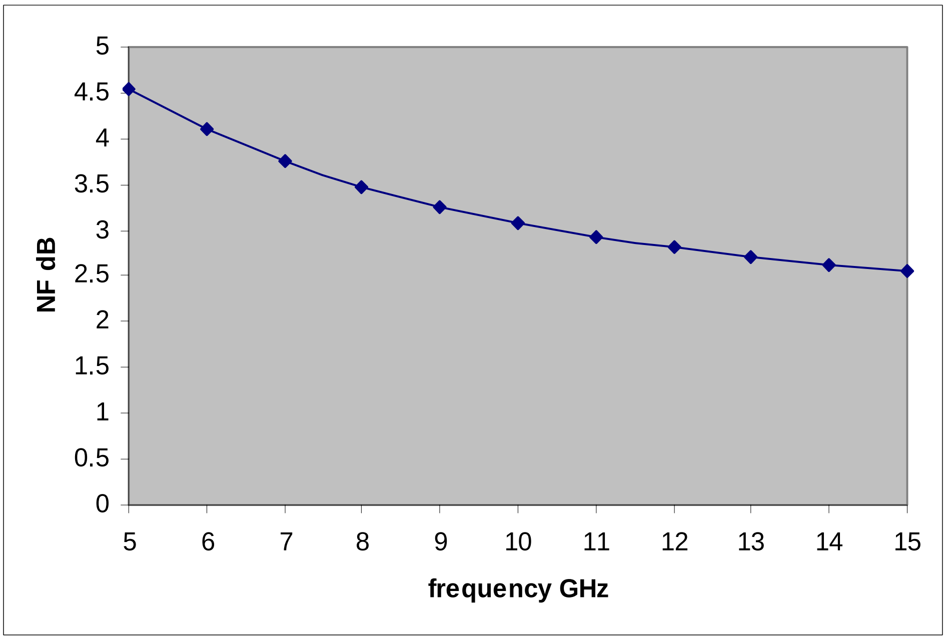

Fig. 9: Minimum noise figure after applying noise at TIA input.

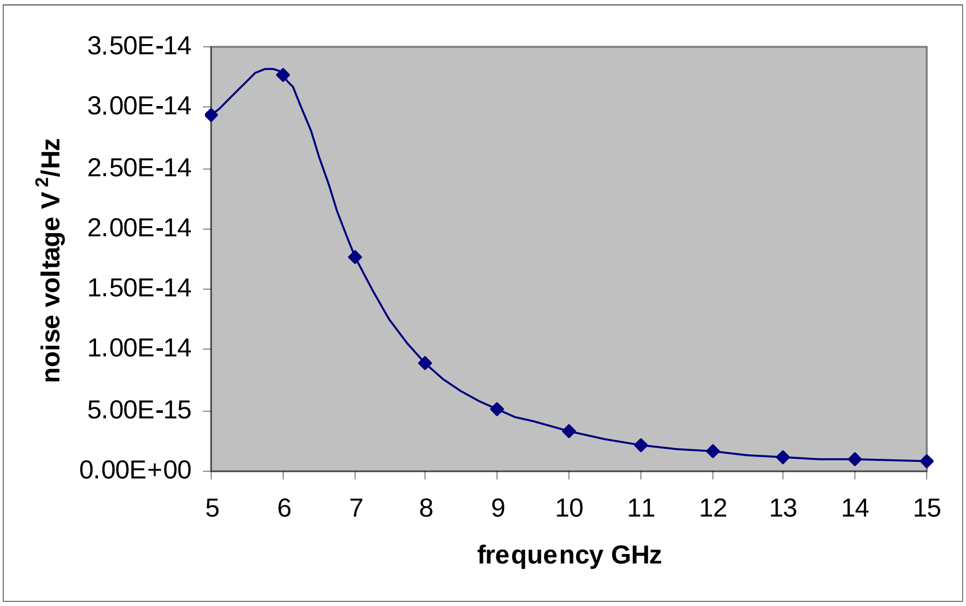

Fig. 10: Noise voltage after applying noise at TIA input.

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