Temperature Dependence of Q and Noise in Monolithic Transformer Fabricated in a Silicon-Germanium/BiCMOS Technology

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Abstract: - In this paper, the first time for demonstrating the analysis of the temperature effect (0 ~ 175^{o}C) upon the quality factor (Q-factor) and noise figure (NF) performance in the transformer which is fabricated on the silicon substrate technology is presented. The experimental data shows that the Q-factor of the primary and secondary coils in the transformer decreased with increasing temperature but showed a reverse behavior at a higher frequency range. The measurement data also shows the variation of quality factor under various temperature conditions influences the maximum available power gain (G_{Amax}) of the transformer, which is the reciprocal of minimum noise figure (NF_{min}) in a passive device.

Key-Words: - Temperature, quality factor, transformer, silicon substrate, G_{Amax}, NF_{min}.

1 Introduction

These days, RF silicon Bipolar, CMOS, and BiCMOS processes have become more and more popular for radio-frequency integrated circuits (RF-IC's) operated in a 5 GHz or even higher frequency bands. The main reasons are the high-performances of the transistors, low-cost, and the high degree of integration with base-band circuits, which satisfies the trade of system on chip (SOC) applications. Especially, the Silicon Germanium (SiGe) technology, not only has the high frequency applications which is similar to the GaAs MMIC technology but also provide the SOC integration ability, has great potential in RF circuit design.

Monolithic RF transformers can be used for on-chip impedance matching, balun implementation and low noise feedback. However, like spiral inductor, the performance of transformers built on conductive silicon are expect to prone to the substrate losses [1]-[6]. Though the issue about the substrate effect in monolithic transformers has been discussed [7], the temperature effect, which leads to the variation of parasitic resistance in transformers and substrate, has not been discussed yet extensively. In the inductor fabricated on the silicon, the quality factor decreased with increasing temperature but showed a reverse behavior at a higher frequency range [8].

Like the inductors, the quality factor of the primary coil and the second coil in the transformers has the same trade. This is because the structure of transformer is similarly constructed by two inductors. Therefore, this phenomenon on the silicon-based integrated transformers also can be explained by the aluminum metallization series with the coils and the eddy current of substrate RF losses under various temperatures.

In addition to the temperature dependence of the Q-factor in transformer fabricated on a silicon substrate, the temperature dependence of the NF (or power loss) in transformers fabricated on a silicon substrate has never been presented. Therefore, in this paper, we also demonstrate the measured temperature dependence (from 0^{o}C to 175^{o}C) of the NF of a transformer.

2 Figure-of-Merit of RF Transformer

The performance of an inductor with regard to its losses can be well described by its quality factor. For transformers, however, the efficiency is described by the maximum available power gain (G_{Amax}, which is the reciprocal of the NF in the passive device), as used for passive RF components [7], which is in terms of the S - parameters. G_{Amax} is given by [9]

$$G_{A\max} = \frac{|S_{21}|}{|S_{12}|}\left(K - \sqrt{K^2 - 1}\right) \quad (1)$$

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{12}S_{21}|} \quad (2)$$

$$\Delta = S_{11}S_{22} - S_{12}S_{21} \quad (3)$$

However, for the purpose of analyzing the transformers performance, we use the alternative expression

$$G_{A\max} = 1 + 2\left(x - \sqrt{x^2 + x}\right)$$
$$x = \frac{\mathrm{Re}(Z_{11})\,\mathrm{Re}(Z_{22}) - [\mathrm{Re}(Z_{12})]^2}{[\mathrm{Im}(Z_{12})]^2 + [\mathrm{Re}(Z_{12})]^2} \quad (4)$$

The Z - parameters of the impedance matrix of the transformer can be represented as

$$\begin{aligned} Z_{11} &= R_P + jwL_P \\ Z_{22} &= R_S + jwL_S \\ Z_{12} &= Z_{21} = R_M + jwL_M \end{aligned} \quad (5)$$

where L_P, L_S and L_M are the primary, secondary, and mutual inductances respectively, and the R_P R_S ,and R_M represent the primary, secondary and mutual resistance of the device. Substitution of (5) into (4), we got

$$x = \frac{1 - k_{\mathrm{Re}}^2}{k_{\mathrm{Im}}^2 Q_P Q_S + k_{\mathrm{Re}}^2} \quad (6)$$

where $Q_p = jwL_P / R_P$ and $Q_S = jwL_S / R_S$ are the quality factors of the primary and secondary coils (another coil is also connected with signal while measuring), respectively. The mutual reactive coupling factor (k_{Im}) and mutual resistive coupling factor (k_{Re}) are given by

$$\begin{aligned} k_{\mathrm{Im}} &= \sqrt{\frac{[\mathrm{Im}(Z_{12})]^2}{\mathrm{Im}(Z_{11})\,\mathrm{Im}(Z_{22})}} \\ k_{\mathrm{Re}} &= \sqrt{\frac{[\mathrm{Re}(Z_{12})]^2}{\mathrm{Re}(Z_{11})\,\mathrm{Re}(Z_{22})}} \end{aligned} \quad (7)$$

A diagram to give the idea of this mutual inductance is shown in Fig. 1.

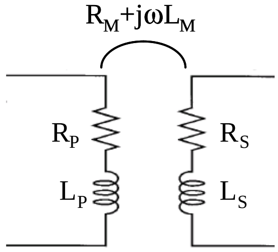

Fig.1 The diagram of the mutual inductance.

From above analysis, we got the conclusion that: increasing the quality factors Q_p and Q_S or the mutual coupling factor k_{Im} and k_{Re} will decrease the x then lead to the increase of G_{Amax}. Therefore, increasing the quality factors of the two coils means that we also improve the transformer quality.

Moreover, the relationship between the noise figure (NF), minimum noise figure (NF_{min}), available power gain (G_A), and maximum available power gain (G_{Amax}) are listed in equations (8) to (11) [10].

$$\begin{aligned} NF &= 10\log(\frac{1}{G_A}) = 10\log(\frac{P_{in}}{P_{out}}) \\ &= NF_{\min} + \frac{4R_n|\Gamma_s - \Gamma_{opt}|^2}{(1 - |\Gamma_s|^2)|1 + \Gamma_{opt}|^2} \end{aligned} \quad (8)$$

$$G_A = \frac{|S_{21}|^2\left(1 - |\Gamma_s|^2\right)}{1 - |S_{22}|^2 + |\Gamma_s|^2\left(|S_{11}|^2 - |D|^2\right) - 2\,\mathrm{Re}(\Gamma_s M)} \quad (9)$$

$$G_{A\max} = \frac{|S_{21}|}{|S_{12}|}\left(K - \sqrt{K^2 - 1}\right) \quad (10)$$

$$NF_{\min} = 10\log(\frac{1}{G_{A\max}}) \quad (11)$$

From these equations, we can see that the noise performance in a transformer could be found by its power gain.

3 Temperature Dependence of Q in Silicon-Based Inductors

Before conferring with the temperature dependence of transformers, it is necessary to have the concept of the quality factor of silicon based inductors under different temperature. In Fig.2, the our experimental data shows that the Q-factor of the silicon based inductors decreased with increasing temperature but showed a reverse behavior at a higher frequency range.

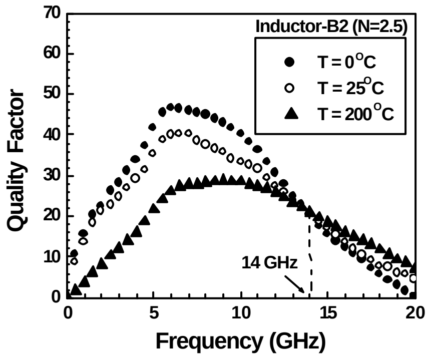

Fig.2 The Q factor of silicon-based inductors under different temperature.

Two primary mechanisms are at work in controlling Q over temperature to cause this phenomenon. The metal metallization, which is in series with the inductor has the positive temperature coefficient, which increase the resistance and thus cause the power loss in the inductor as the temperature increases. This will leads to the decrease of Q. The substrate resistivity, which is in parallel with the inductance, also has a positive temperature coefficient. This will decrease the power loss in the substrate as the temperature increase, causing the increase of Q.

At low frequencies (below 14 GHz), the primary power loss in the inductor is in the series resistance of the metal. This results from the capacitance to substrate presenting a high impedance to the signal present in the inductor, causing almost all of the current to flow in the inductor metallization. At high frequencies (above 14 GHz), where the capacitance to substrate presents a lower impedance path, and the feedthrough capacitance increasingly shunts out the metal series resistance, the power lost in the substrate begins to dominate. [8].

4 Temperature Dependence of Q and Noise in Silicon-Based Transformer

From the reason of the similarity between coils in a transformer and inductors, we predict that there will be the same phenomenon as described in the section two in the coils. In order to study the effect of temperature dependence of Q and noise in transformer characteristics, the transformer (see Fig. 3) was fabricated in TSMC 0.35um SiGe Bi/CMOS.

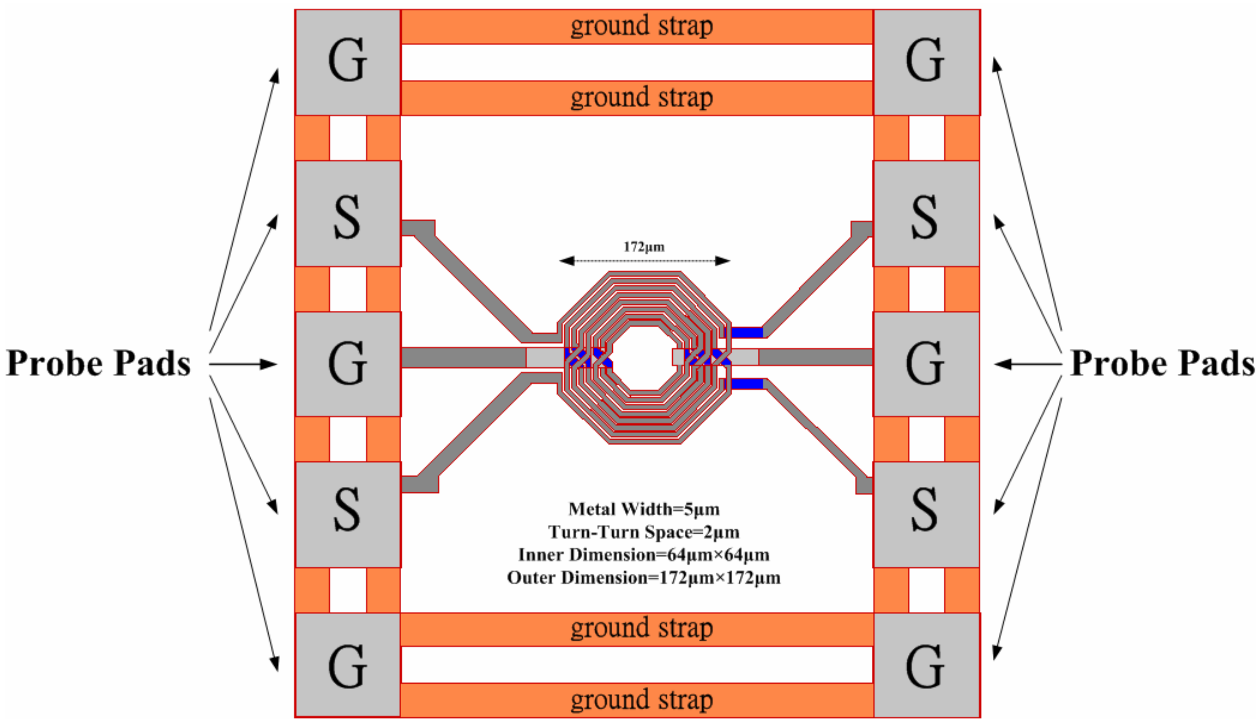

Fig. 3 Integrated spiral RF transformer, with two turns for both coils.

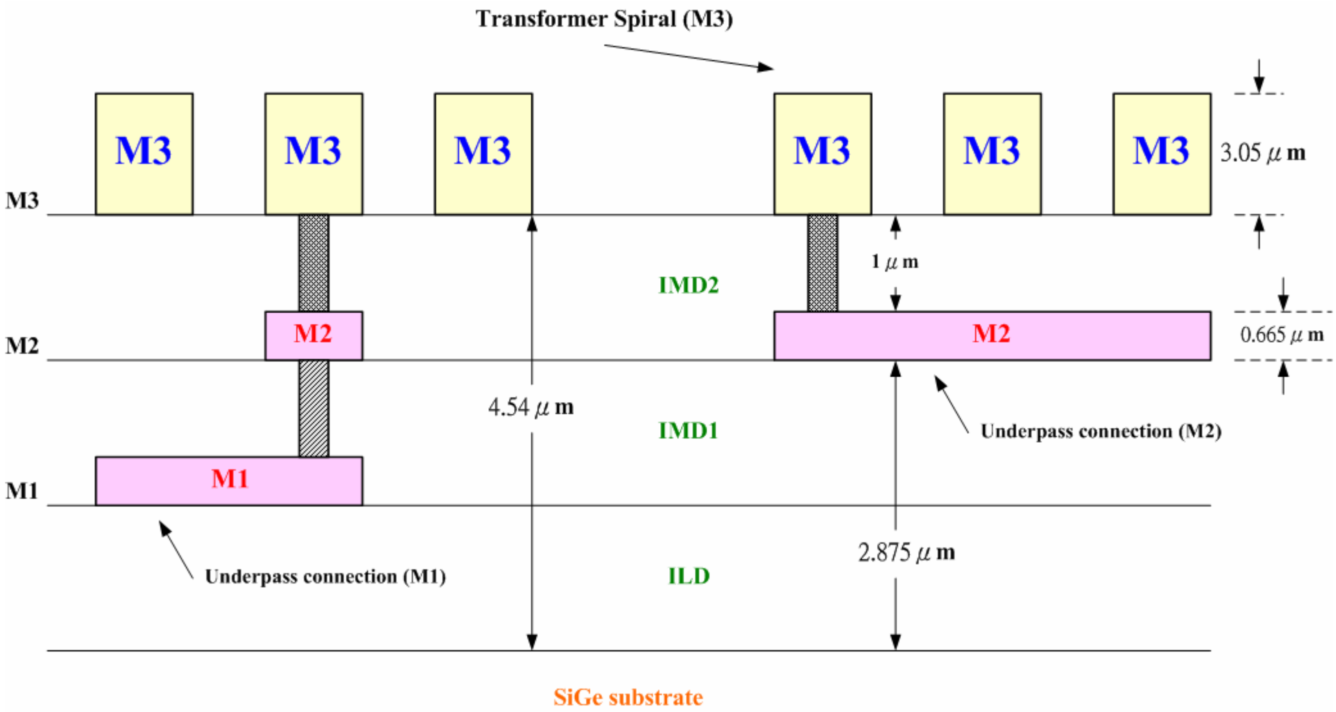

Fig. 4 Transformer cross section schematic.

Both coils of each transformer used in the experiment were built at M3, and the underpasss connections were built at M2 Fig. 4 as shows.

The measurement data under various temperatures are shown in the following figures. The Q factor of the primary coil (Q_P) of the spiral RF transformer is shown in Fig. 5, and the special shot of Q factor inverse phenomenon is magnified in Fig. 6. The Fig. 7. and Fig. 8 are the Q factor of the secondary coil (Q_S) . The extracted primary, secondary and mutual resistances are shown in Fig.9 to Fig.11, and inductances are shown in Fig. 12 to Fig. 14, respectively. The extracted mutual coupling coefficients are in Fig. 15 and Fig. 16. Finally, the extracted minimum noise figure (NF_{min}) and maximum available power gain (G_{Amax}) and their magnified special shot at the inverse phenomenon at high frequency are also shown in Fig.17 and Fig 20. As can be seen, the G_{Amax} decreases with the increasing of temperature, and leads NF_{min}, which is also interactive with Q_P and Q_S, to have positive coefficient with temperature below 13 GHz. Nearly at 13 GHz, G_{Amax} and NF_{min} also have the inverse phenomenon because the eddy current in the silicon-based substrate is the predominant at high frequency range.

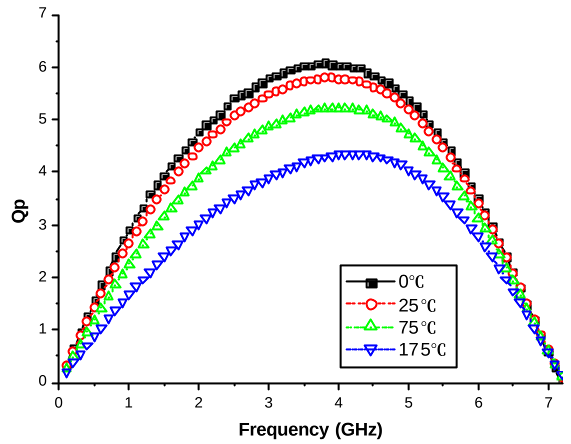

Fig. 5 The Q factor of the primary coil of the spiral RF transformer.

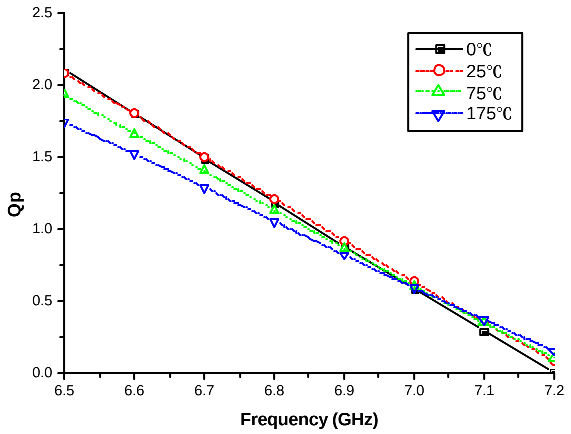

Fig. 6 The Q factor of the primary coil decreased with increasing temperature but showed a reverse behavior at a higher frequency range.

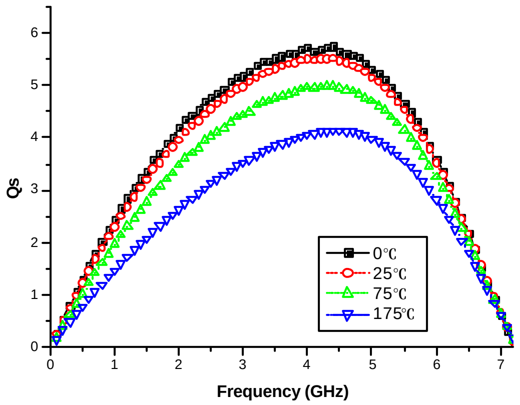

Fig. 7 The Q factor of the second coil of the spiral RF transformer.

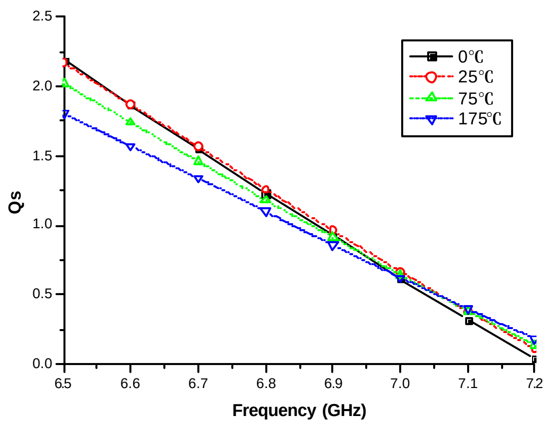

Fig. 8 The Q factor of the secondary coil decreased with increasing temperature but showed a reverse behavior at a higher frequency range.

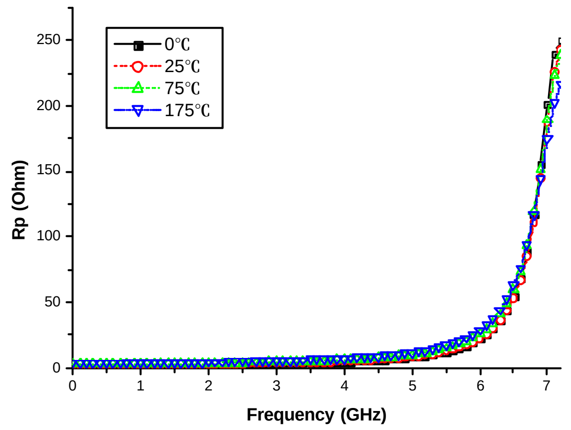

Fig. 9 The extracted resistance of the primary coil of the spiral RF transformer.

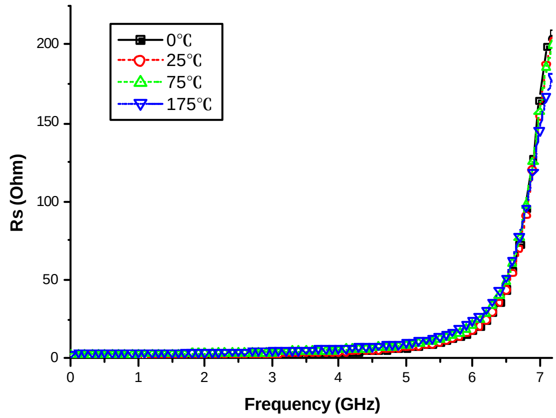

Fig. 10 The extracted resistance of the secondary coil of the spiral RF transformer.

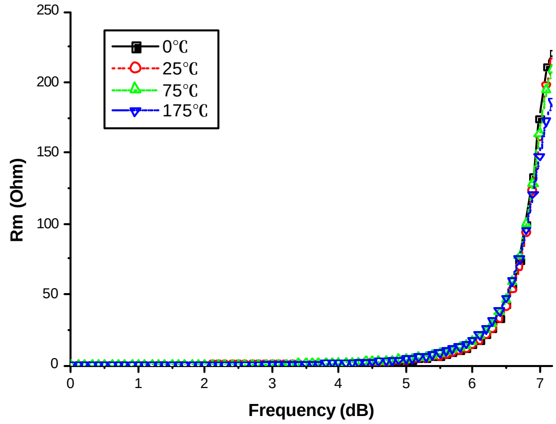

Fig. 11 The extracted mutual resistance of the spiral RF transformer.

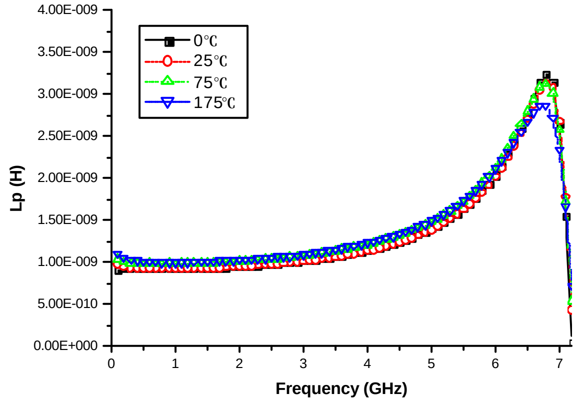

Fig. 12 The extracted inductance of the primary coil of the spiral RF transformer.

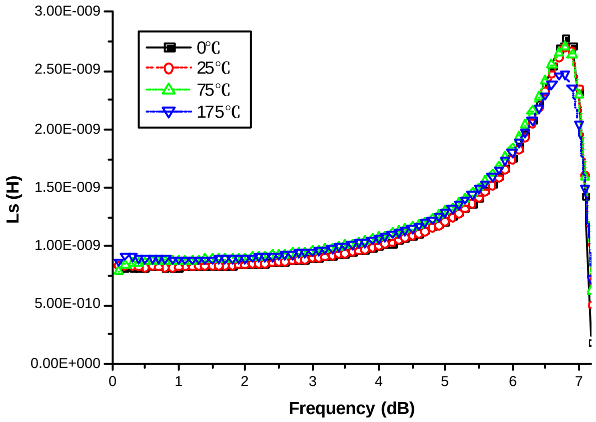

Fig. 13 The extracted inductance of the secondary coil of the spiral RF transformer.

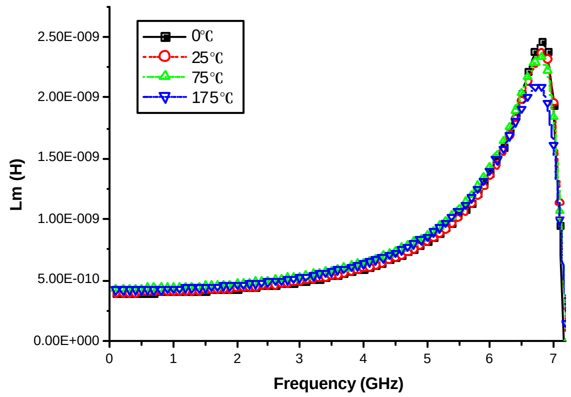

Fig. 14 The extracted inductance of the mutual inductance of the spiral RF transformer.

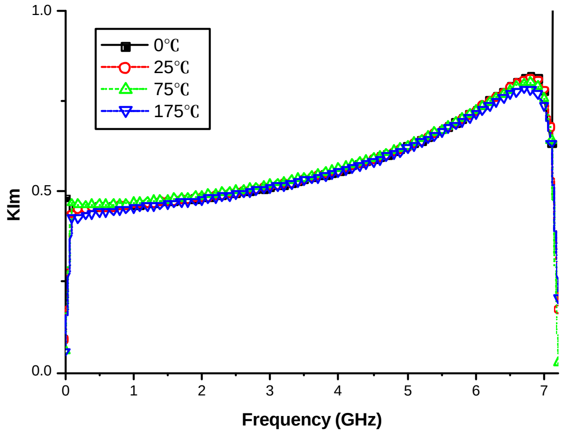

Fig. 15 The extracted mutual reactive coupling factor (k_{Im}) of the spiral RF transformer.

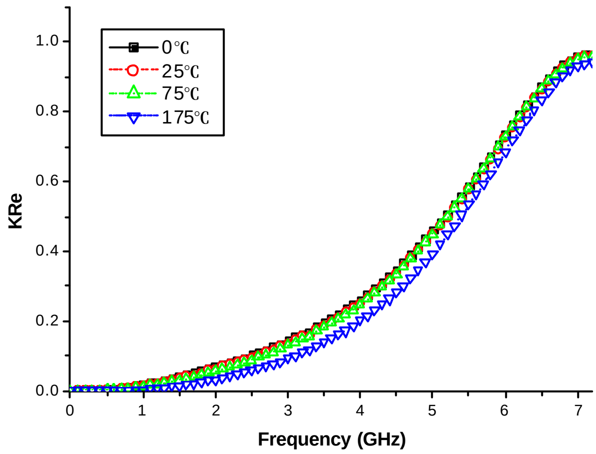

Fig. 16 The extracted mutual resistive coupling factor k_{Re})of the spiral RF transformer.

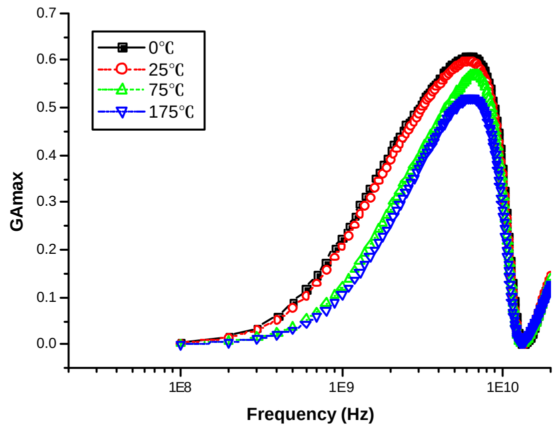

Fig. 17 The extracted maximum available power gain (G_{Amax}) of the spiral RF transformer.

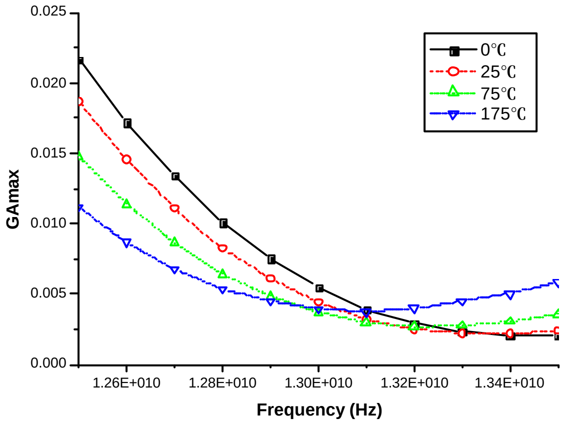

Fig. 18 The maximum available power gain (G_{Amax}) decreased with increasing temperature but showed a reverse behavior at a higher frequency range.

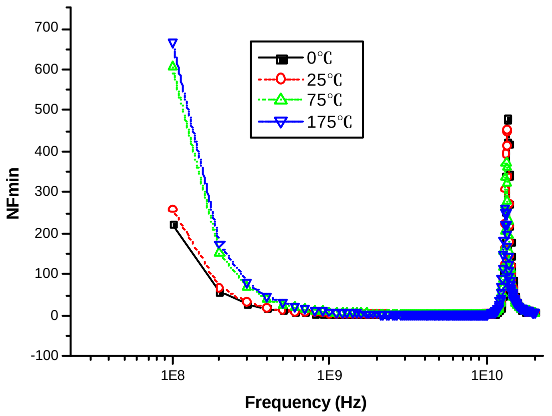

Fig. 19 The extracted minimum noise figure (NF_{min}) of the spiral RF transformer.

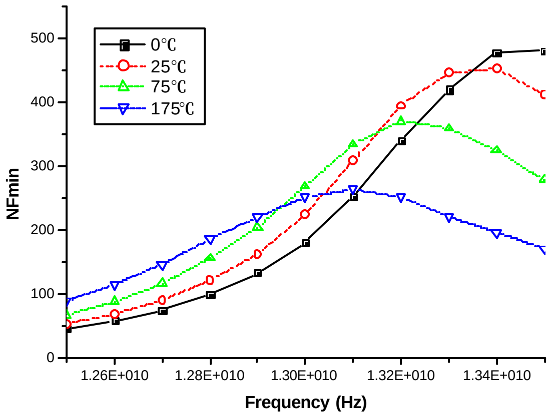

Fig. 20. The minimum noise figure (NF_{min}) increases with increasing temperature but showed a reverse behavior at a higher frequency range

5 Conclusion

In this paper, we demonstrated and analyzed the temperature effect (0 ~ 175°C) on the quality factor of silicon- based transformer. The quality factor of the two coils in a transformer, like silicon-based spiral inductors, decreased with increasing temperature but showed a reverse behavior at a higher frequency range. In additional, the temperature effect upon the minimum noise figure (NF_{min}) and maximum available power gain (G_{Amax}) are also demonstrated, which also have the inverse phenomenon at nearly 13GHz due to the eddy current effect will become the predominate at high frequency range.

The knowledge of the temperature dependences of Q and NF can facilitate RF-IC's designers to implement less temperature-sensitive fully on-chip low-power-consumption LNA's and other RF-IC's.

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