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Leakage current effect on fixed and tunable solenoid RF MEMS inductors

Nizar Habbachi

Microelectronics and Instrumentation Laboratory, Faculty
of Sciences of Monastir, University of Monastir, 5000
Monastir, Tunisia,
habbachinizar@yahoo.fr

Hatem Boussetta

Institut Préparatoire aux Etudes d'Ingénieurs de Monastir,
Rue Ibn Eljazzar - 5019 Monastir Tunisia, and he is with
Microelectronics and Instrumentation Laboratory, Faculty
of Sciences of Monastir, University of Monastir, 5000
Monastir, Tunisia,
hatem_boussetta@yahoo.fr

Mohamed Adel Kallala

Military Research Centre, Tunis, and he is with
Microelectronics and Instrumentation Laboratory, Faculty
of Sciences of Monastir, University of Monastir, 5000
Monastir, Tunisia,
Adel.kallala@gmail.com

Ali Boukabache

Laboratory for Analysis and Architecture of Systems,
CNRS , LAAS, 7 avenue du Colonel Roche, 31077
Toulouse, France, and he is with the University of Toulouse,
1077 Toulouse, France,
aboukaba@laas.fr

Patrick Pons

Laboratory for Analysis and Architecture of Systems,
CNRS, LAAS, 7 avenue du Colonel Roche, 31077
Toulouse, France,
ppons@laas.fr

Kamel Besbes

Center for Research on Microelectronics &
Nanotechnology, CRMN Sousse TechnoPark, BP 334
Sahloul Sousse, Tunisia, and he is with Microelectronics
and Instrumentation Laboratory, Faculty of Sciences of
Monastir, University of Monastir, 5000 Monastir, Tunisia,
kamel.besbes@fsm.rnu.tn

Abstract— This paper investigates the performances of fixed and tunable solenoid RF MEMS inductors for two silicon substrates: regular and etched. We have modeled the current density distribution in silicon substrates and then in NiFe plate using FEM numerical tool. Moreover, we have studied the inductors performances in responses of frequency variation from 100 MHz to 30 GHz. The best quality factor and resonant frequency values are respectively $Q_{max} = 19$ and $F_{res} = 15$ GHz when substrate leakage current is reduced. In addition, the obtained tuning range increases and reaches $Tr = 132.8\%$ at 10 GHz instead of $Tr = 96.8\%$ at 5 GHz when the silicon substrate is etched.

Keywords—RF MEMS; solenoid; inductor; tunable; microwave, eddy current.

I. INTRODUCTION

RF MEMS inductors have drawn much attention owing their versatility in microwave domain [1]. Several actuation techniques were proposed in order to ameliorate the RF MEMS devices performances [2-7]. In all contributions, RF designers need to increase the tuning range, the quality factor, and the resonant frequency. The most reported tunable RF MEMS inductors are based on spiral geometry modification [3-4]. An external actuation manipulator imbedded in the inductor center is used to control the core height [3]. The inductor performances are characterized at 2GHz for a total distance variation of 150 μm . The tuning range and the quality factor are respectively $Tr = 3\%$ and $Q = 2$. A more efficient tunable MEMS inductor using the dilatation of spirals turns under the joule effect is investigated in [4]. Indeed, the variation of spirals positions with respect to the substrate makes it possible to increase the quality factor and the resonance frequency. The characterization of this structure shows a tuning range of $Tr = 18\%$ and a quality factor $Q = 13$ with a high frequency resonance $F_{res} = 15$ GHz.

In this paper, we present the effect of the leakage current on solenoid RF MEMS inductors performances: fixed and tunable. At the first part, we present our main structure with detailed dimensions in 3D perspective. Then, we investigate the current distribution in two cases of substrate: conventional and etched. At the second part, we discuss the displacement of ferromagnetic thin film inner solenoid core on inductor performances. The obtained results demonstrate the importance of etched substrate in the improvement of the response of our tunable inductor.

II. RF MEMS FIXED INDUCTOR

A. Structure responses with regular substrate

We have designed seven turns core using copper metal due to his high electrical conductivity $\sigma = 57.10^6$ S/m. The substrate is a high resistive silicon $\sigma = 3$ S/m and possess a relative permittivity $\epsilon = 11.2$. The Fig 1 illustrates the 3D perspective of our structure accompanied with detailed dimensions:

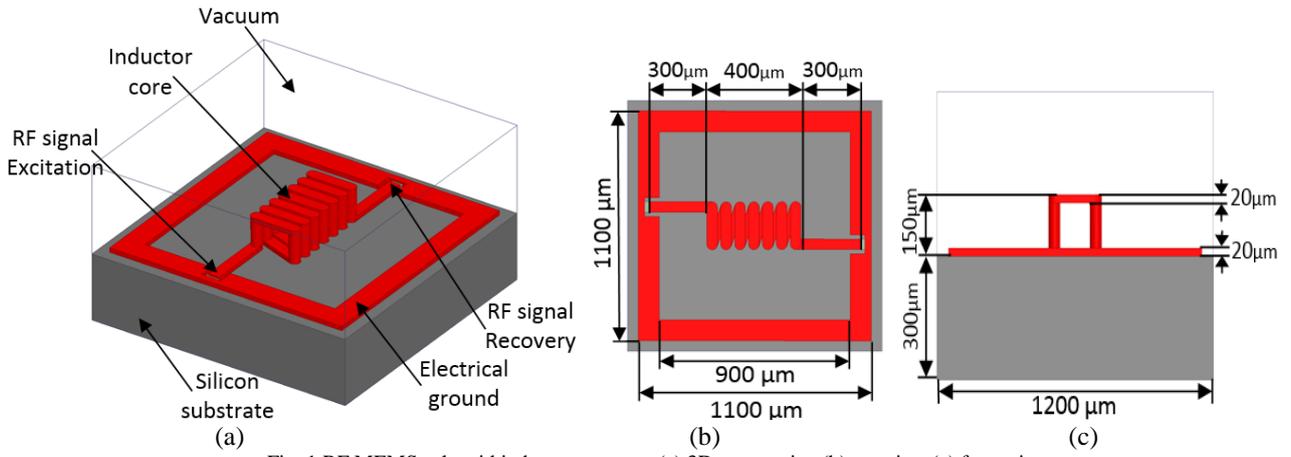


Fig. 1 RF MEMS solenoid inductor structure (a) 3D perspective (b) top view (c) front view.

The response of RF inductors depends on geometrical dimension and electrical propriety of used materials. The inductance and the quality factor values are extracted from the Y parameters using the equations below:

$$L(f) = \frac{\text{Im}(1/Y_{11})}{2 * \Pi * f}$$

$$Q(f) = \frac{\text{Im}(Y_{11})}{\text{Re}(Y_{11})}$$

The Fig 2 presents the RF performances of our inductor for a frequency range from 100 MHz to 30 GHz:

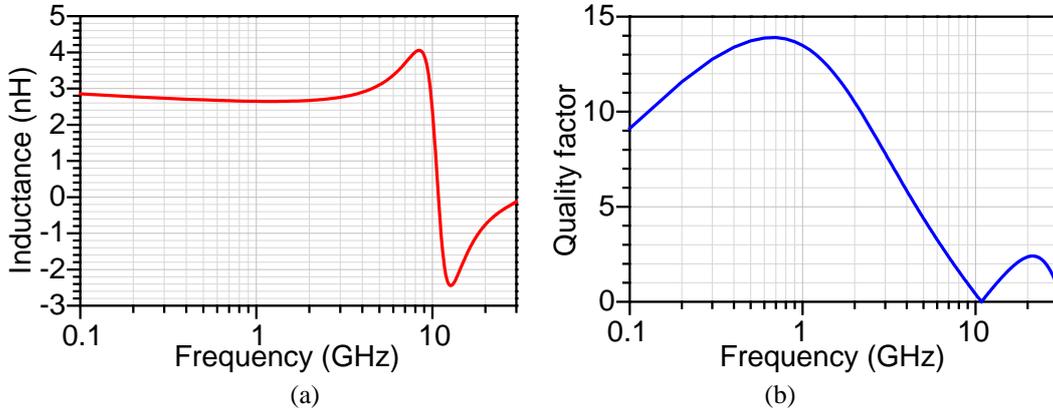
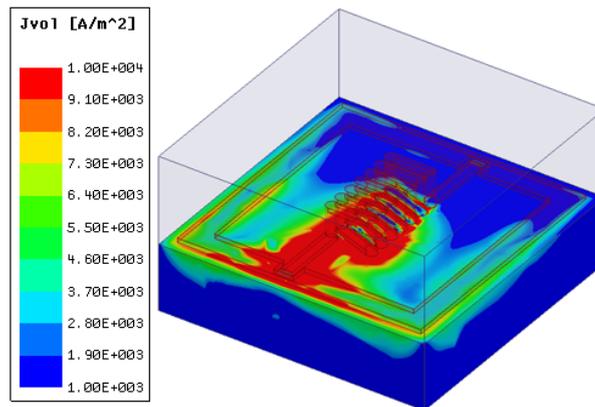


Fig. 2 Inductor performances in response of frequency variation (a) inductance value (b) quality factor.

The Fig 2.a shows a good stability of the inductance value until 8 GHz. Indeed, the inductance value is comprised between 2.8 nH and 4 nH and the resonant frequency reaches 10 GHz. Moreover, the quality factor is greatly higher than spiral RF inductors [3-4]. The maximal value of the quality factor $Q_{\text{max}} = 14$ is obtained at 700 MHz. The performance of the RF inductor is also related to the substrate losses as the eddy current.

We have investigated the current distribution in the silicon substrate at 5 GHz and in response of other frequencies: 100 MHz, 10 GHz, 20 GHz, 30 GHz.



(a)

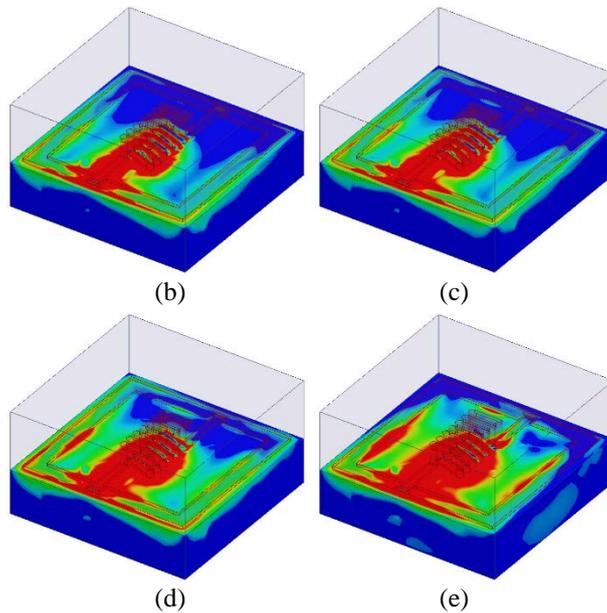


Fig. 3 Distribution of electrical current density in silicon substrate for different frequencies (a) aim frequency 5 GHz (b) 100 MHz (c) 10 GHz (d) 20 GHz (e) 30 GHz.

As we can see in Fig 3.a, the maximum amount of distributed current is localized underneath the excitation port and the inductor's core. In addition, the substrate leakage current rises in response of frequency variation as illustrated in fig 3(b-e).

B. Structure responses with etched substrate

In the previous part, we have concluded that the silicon substrate is condemned by the excessive leakage current that could decrease the RF performances of our inductor. Therefore, we have etched the volume underneath the core of solenoid inductor as shown in Fig 4.

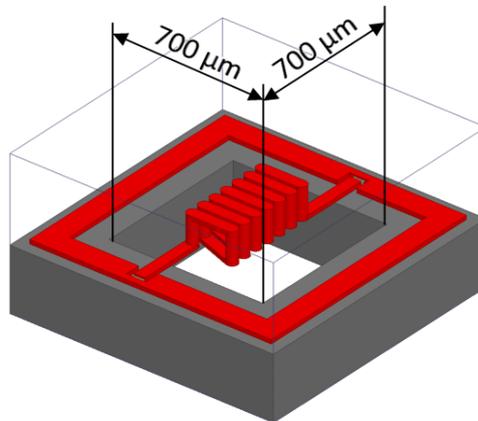


Fig.4 3D perspective of RF MEMS solenoid inductor structure with etched substrate.

The Fig 5 illustrates the RF performances of the new solenoid inductor in response of frequency variation from 100 MHz to 30 GHz:

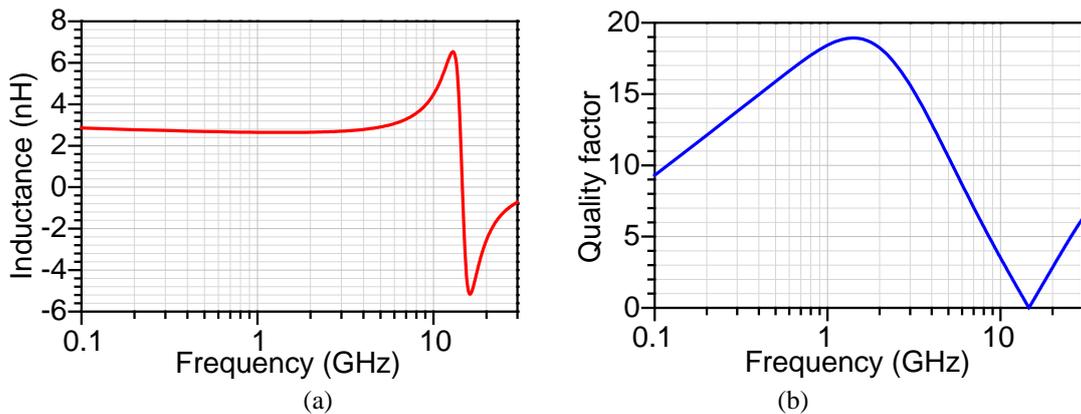


Fig. 5 Inductor performances in response of frequency variation (a) inductance value (b) quality factor.

It is clearly seen at the Fig 5.a that resonant frequency is increased and reaches 15 GHz. In addition, the inductance value is amplified and it is comprised between 2.4 nH and 6.5 nH. The quality factor is greatly ameliorated and reaches $Q_{\max} = 19$ at 1.5 GHz (Fig 5.b). We have investigated the new current distribution as shown in Fig.6:

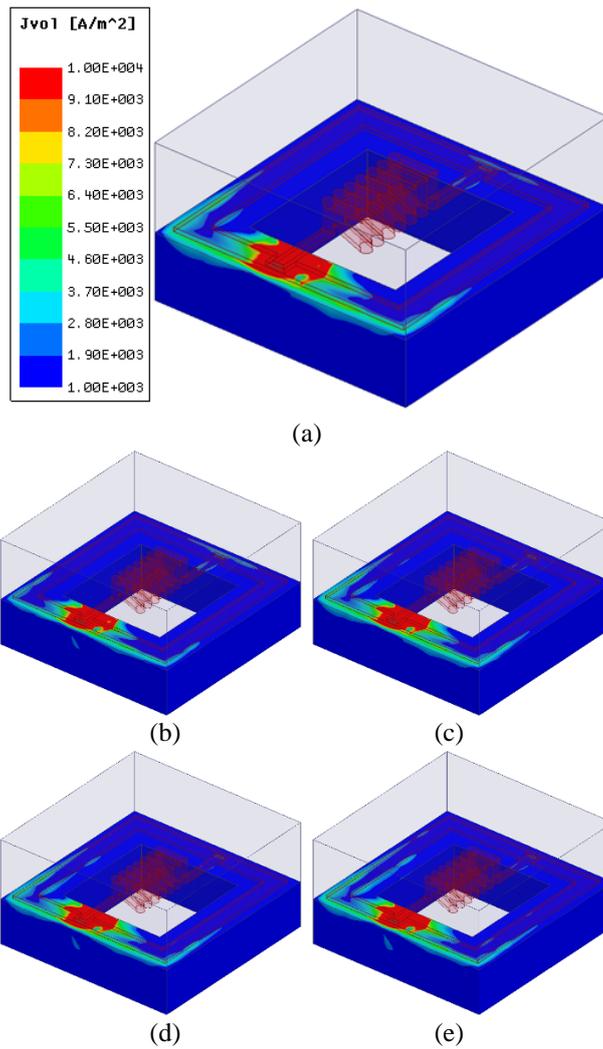


Fig. 6 Distribution of electrical current density in silicon substrate for different frequencies (a) aim frequency 5 GHz (b) 100 MHz (c) 10 GHz (d) 20 GHz (e) 30 GHz.

At 5 GHz (Fig 6.a), the distributed current is localized at the excitation zone and it is almost negligible at the other parts of the substrate. Moreover, as we can see in Fig 6(b-e) the amount of the leakage current is became less sensible to the frequency variation. Indeed, the eddy current possesses almost the same repartition from 100 MHz to 30 GHz. Consequently, we can conclude that the inductor performances are limited by the ability of lakage current penetration in silicon substrate.

III. RF MEMS TUNABLE INDUCTORS

A. Current distribution with regular substrate

The variation principle of our inductor is based on the modification of the solenoid core permeability in response of NiFe plate displacement. We have investigated the distribution of electrical current density on the ferromagnetic thin film for five positions. The Fig 7 illustrates the obtained results at 5 GHz with 100 μm successive step for each position:

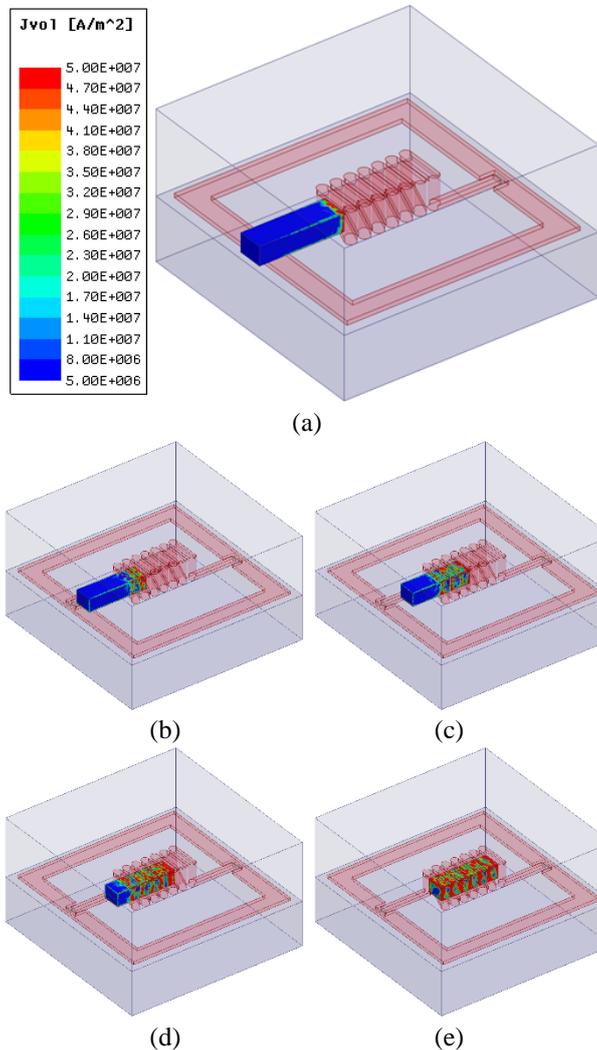


Fig. 7 Distribution of electrical current density in NiFe plate at 5 GHz (a) POS1 (b) POS2 (c) POS3 (d) POS4 (e) POS5.

As we can see in the Fig 7.a, a high level of distributed current appears in the head of the ferromagnetic thin film when it is placed at the front of the solenoid core. We have moved the NiFe plate by 100 μm steps and we observed an increasing current density as illustrated in Fig 7(b-e). Indeed, the magnetic flux prevailing inner solenoid core induces electrical current in metal plate and the coupled magnetic field changes in response of the permeability of the ferromagnetic thin film.

B. Performances variations with regular substrate

Furthermore, in order to evaluate the effect of the NiFe plate displacement on the inductor performances we have drawn the quality factor and inductance value variations.

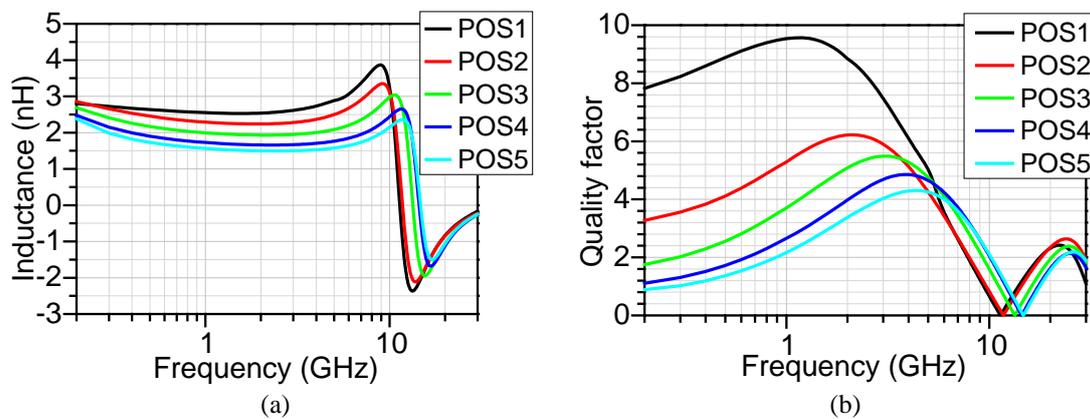


Fig. 8 Inductor performances in response of frequency variation for five positions of NiFe plate (a) inductance value (b) quality factor.

The Fig 8.a illustrates the inductance variation for the frequency range of 100 MHz to 30 GHz. It is clearly seen that the inductance decreases in response of NiFe plate penetration in solenoid core. At 5 GHz, the inductor value is comprised between $L = 3.09$ nH without actuation to $L = 1.57$ nH when the NiFe reach the last position. Therefore, we obtain an importante inductance tuning range

that reaches $Tr = 96.81\%$. In addition, the quality factor fall down and became minimal $Q_{min} = 4.5$ when the ferromagnetic thin film occupy the whole solenoid core at 5GHz.

C. Current distribution with etched substrate

We have used the same principle of variation with MEMS inductor in order to study the effect of etched silicon substrate on inductor performances. The Fig 9 shows the distribution of electrical current density on NiFe plate for five positions at 5 GHz:

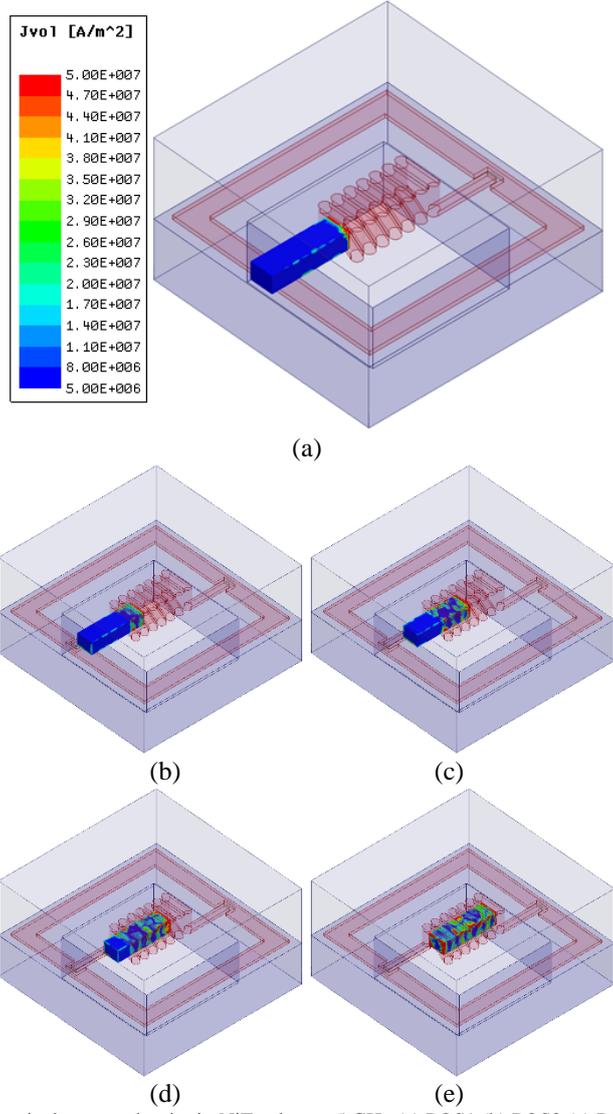


Fig. 9 Distribution of electrical current density in NiFe plate at 5 GHz (a) POS1 (b) POS2 (c) POS3 (d) POS4 (e) POS5.

For the first position of the NiFe plate (Fig 9.a), we observe almost the same current repartition as obtained in the previous study shown in Fig 7.a. Nevertheless, the current density clearly decreases compared to previous results when the ferromagnetic thin film penetrates the solenoid core. We can conclude that magnetic flux inner solenoid core is also influenced by the eddy current occurs in silicon substrate.

D. Performances variations with etched substrate

We have investigated the inductance and the quality factor variations for five NiFe plate positions. The Fig 10 illustrates the obtained results for frequency range from 100 MHz to 30 GHz:

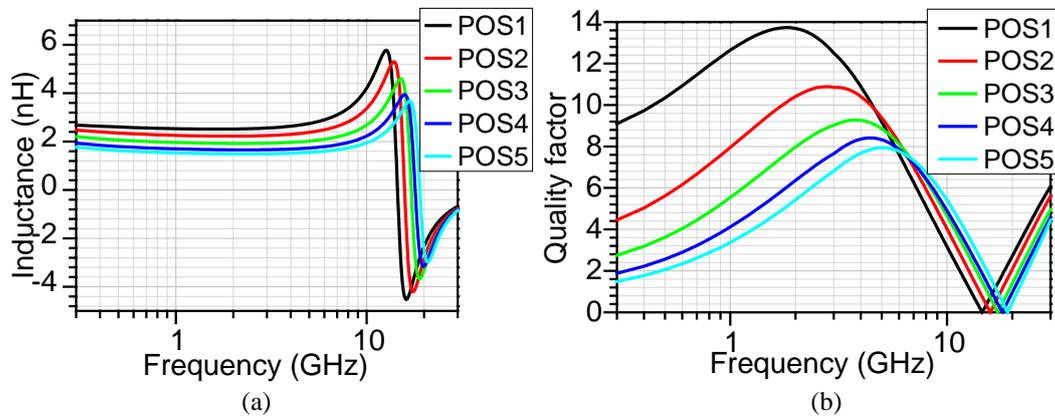


Fig. 10 Inductor performances in response of frequency variation for five positions of NiFe plate (a) inductance value (b) quality factor.

The inductance curves illustrate a high resonant frequency accompanied with the diminution of inductor value in response of the ferromagnetic thin film displacement (Fig 10.a). The total inductance variation at 5 GHz is comprised between $L = 2.9$ nH and $L = 1.55$ nH that leads to $Tr = 87\%$ and rise up to $Tr = 132.81\%$ at 10 GHz. Moreover, the minimal quality factor value increases and reaches $Q = 8$ at 5 GHz.

IV. CONCLUSION

Two different solenoid RF MEMS inductors are designed and studied: fixed and variable. In first case, we have investigated the current density distribution in silicon substrate and we have discussed the inductors performances in regular and etched silicon substrate. The obtained results show an important amelioration of quality factor and resonant frequency when silicon substrate is etched due to the diminution of substrate leakage current. In second case, we have discussed NiFe plate penetration inner the solenoid core in two substrates states. Once more, the performances of tunable inductors are also clearly ameliorated with etched substrate.

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