A Core-Displacement Method Tunable Inductor using Micro-Electro-Mechanical-Systems Technology

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Abstract

In this paper, we introduce a new electrostatic tunable inductor with a simple tuning mechanism employing Micro-Electro-Mechanical-Systems. The proposed structure consists of a spiral inductor, a NiFe core material which is attached to a polysilicon support and electrodes of the electrostatic actuation. The inductance tuning mechanism is based on core-displacement and skin effect. When the electrostatic voltage is applied, the core is moved up and distance between the inductor and the core is increased, so magnetic stored energy of inductor is changed and hence the inductance tuning is achieved. The structure is simulated employing finite element method software such as COMSOL and ANSOFT HFSS. According to electromagnetic and electrostatic simulation results, a 69% tuning range at the frequency of 8 GHz and a quality factor of 13.3 has been achieved which is very suitable for RF applications. The simulation results show an electrostatic actuation voltage of the 25.3 V for the designed structure.

Keywords: Core Displacement, Electrostatic, MEMS, RF Applications, Tunable Inductor

1. Introduction

In recent two decades, diversity applications of tunable passive components (inductors and capacitors) such as low phase noise Voltage Controlled Oscillators (VCO), LC tunable filters, impedance matching networks, Frequency Agile Radios, RF wireless applications, phase shifters, low noise amplifiers and so on have been attractive subject for the analog communication designers and researchers. Tunable Micro-Electro-Mechanical-Systems (MEMS) inductors are one of the main critical components in RF applications because of its good broad range tuning frequency capability and simple and diversity tuning methods1-6. A number of methods for tunable micro-inductor have been reported in the literature7. These methods are classified into two main groups: discrete and continuous tuning. The discrete tuning of inductors is achieved by changing the length or configuration employing MEMS8 or MOSFET switches9. This type of tunable inductors have large resistive loss because of switch structures, therefore its quality factor is reduced. Alternatively, the continuous tuning of inductors is realized by changing in the magnetic properties of core10,11 or displacing the core12-14. The complicated actuation mechanism and fabrication process of these inductors are their drawbacks. However, the quality factor and inductance tuning range can be increased.

In this paper, we introduce a new structure which can be tuned using magnetic core displacement method. The new design for the tunable inductor is explained in the section 2. Section 3 covers the simulation results.

2. Proposed Tunable Inductor

It is well known that given the magnetic field, the self-inductance ($L$) of an inductor can be calculated from the Equation (1).

$$L = \frac{2W}{I^2}$$  \hspace{1cm} (1)
Where $W$ is the magnetic energy and $I$ is the current. When the magnetic energy of an inductor is changed the tunable inductor is possible.

Based on the core-displacement idea for tunable inductors, we proposed a new structure which is depicted in Figure 1.

As mentioned in Figure 1, the proposed structure consists of a spiral type inductor (copper material), a magnetic core (NiFe) which is attached to a support (polysilicon), two low-resistive substrates (glass and silicon substrate) and electrostatic actuation system. The spiral inductor and the electrostatic actuation system are located on silicon and glass substrate respectively. The spiral inductor is formed on a thin dielectric layer to decrease the parasitic capacitances between the substrate and the inductor and prevent the resonance effect.

Because of the fast mechanical response, low power consumption and scalability of electrostatic actuation, it is suitable as actuation mechanism of proposed tunable inductor.

The spiral inductor is shown in Figure 2. Based on this figure, the spiral inductor consists of 3 turn square-shape conducting coil which has 10μm width and 10μm height. The space between the coils is 10μm.

2.1 Tuning Mechanism

The Mechanism of inductance tuning is based on change in the magnetic energy of the spiral inductor employing core displacement method. Due to the skin effect, the inductance tuning has different behavior in low and high frequencies. At low frequencies, when the magnetic core is close to the spiral inductor, the majority of the magnetic flux lines pass through the core and hence the self inductance becomes high. When the actuation is applied, the core is moved up and distance between the core and inductor is increased, a lot of the magnetic flux lines pass through the air and only a few pass through the core, the magnetic flux density of inductor and therefore the inductance is decreased. This phenomenon is depicted in Figure 3.

![Figure 3](image-url) Magnetic Flux Density of tunable inductor at low frequencies. (a) Displacement = 0 and (b) Displacement = 10μm.
As depicted in Figure 4, at high frequencies when the core displacement is zero, because of the skin effect, the magnetic flux lines cannot pass through the magnetic core and pass through the available traces, the reluctance is increased, hence the self inductance is decreased. When the distance between the core and inductor is increased, the magnetic flux pass through the short traces, the reluctance is decreased and hence the inductance is increased.

2.2 Electrostatic Actuation System

Suppose that the Voltage (V) is applied between two plates. If one plate is fixed and the other can be moved, then the movable plate is moved to the fixed plate and contact between two plates is achieved. The required voltage for this purpose is known as pull-in voltage and is expressed as:

\[ V_p = \frac{8k g_0^3}{27\varepsilon_0 A} \]  

(2)

Where, \( V_p \) is the pull-in voltage, \( k \) is the mechanical spring constant of the electrodes, \( g_0 \) is the gap between upper and lower electrode; \( A \) is the effective area of the electrode and \( \varepsilon_0 \) is the air permittivity. For a fixed-free cantilever beam, the spring constant is as:

\[ K = \frac{Ewh^3}{4L^4} \]  

(3)

Where, \( E \) is the young's modulus, \( w, h \) and \( L \) is width, thickness and length of the beam respectively. To reduce the required voltage we have some selections, such as decreasing in \( E, w \) or \( h \) and increasing in length of the beam. However it should be note that because of the limitation in the structure area, the length of the beam cannot be so large, and because of limitation in the yield stress of the beam material, the thickness of the beam cannot be very small. The tradeoff between these parameters can be achieved using analytical and simulation results. The schematic of the proposed electrostatic system is shown in Figure 5.

3. Simulation Results

To realize and optimize the analysis results, the structure is simulated with FEM software such as COMSOL Multiphysics and ANSOFT HFSS™. The COMSOL software is employed to find the tuning range and the required electrostatic voltage and the HFSS results help us to find the frequency response of the designed structure.

3.1 Electromagnetic Simulation

To find the tuning range of the proposed structure, we simulate two structures, one when the distance between the inductor and the core is 5µm and no applied voltage and the other when the distance is 15µm. The properties of the inductor and the core material are depicted in Table 1.

![Figure 4](image)

**Figure 4.** Magnetic Flux Density of tunable inductor at high frequencies. (a) Displacement = 0 and (b) Displacement = 10µm.

![Figure 5](image)

**Figure 5.** The electrostatic actuation system for the proposed tunable inductor.
The tuning range of the proposed inductor is shown in Figure 6. Note that this simulation is accomplished in DC frequencies and a 13.8% tuning ratio is achieved.

### 3.2 Electrostatic Simulation

To access the actuation voltage of the designed cantilever beam, the electrostatic simulation is accomplished. To realize the low actuation voltage, different simulations with various beam lengths are done. Finally, the length of 2000µm is selected. Because of good mechanical properties of the polysilicon, it is the best candidate for the beam material. The material mechanical properties for the electrostatic simulation are shown in Table 2.

The electrostatic simulation is accomplished in the MEMS module of COMSOL software. Figure 7 and Figure 8 shows the required voltage to 10µm deflection the cantilever beam and the stress distribution on the beam, respectively.

Based on the electrostatic simulation results, the required actuation voltage for the core displacement is 25.35 V. The maximum stress distribution on the beam is 7.32MPa which is very smaller than the yield stress of the polysilicon (1 GPa).

### 3.3 Frequency Simulation

The frequency simulation is employed to find the best frequency response of the proposed tunable inductor

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**Table 1.** Electromagnetic properties

| Material          | Conductivity (S/m) | Relative Permeability |
|-------------------|--------------------|-----------------------|
| Spiral Inductor (Copper) | 58.1e6         | 1                     |
| Core (NiFe)       | 5e6                | 500                   |

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**Table 2.** Mechanical properties

| Parameter                | NiFe  | Polysilicon |
|--------------------------|-------|-------------|
| Young's Modulus (GPa)    | 152   | 153         |
| Poisson Ratio            | 0.27  | 0.21        |
| Density (kg/m³)          | 7860  | 2330        |
| Length (µm)              | 240   | 2000        |
| Width (µm)               | 220   | 220         |
| Thickness (µm)           | 5     | 10          |
| Relative Permittivity (F/m) | 1     | 4.6         |
| Permeability             | 500   | 1           |
| Conductivity (s/m)       | 5e6   | 10          |

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**Figure 6.** The tuning range of the proposed tunable inductor.

**Figure 7.** The voltage-displacement diagram of the proposed electrostatic actuation.

**Figure 8.** The stress distribution on the cantilever beam of electrostatic actuation.
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Q = \frac{E_{stored}}{E_{Dissipated}} = \frac{\text{image}(Z)}{\text{Real}(Z)} = \frac{\text{coL}}{R} \quad \text{Eq. 4}
\]

As depicted in Figure 10, the quality factor of the inductor is 13.3 at 8 GHz and in this frequency a 69% tuning range can be achieved.

4. Conclusion

A novel electrostatic MEMS tunable inductor for RF application based on core displacement tuning mechanism is designed and simulated. The proposed design has the simple tuning mechanism, the simple electrostatic actuation, a reasonable tuning range and a significant quality factor at high frequency (RF) applications. FEM simulation results satisfy all designed requirements.

Figure 10. The Quality factor of the tunable inductor. (a) Before core displacement and (b) after core displacement.

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6. References

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