MEMS-based tunable meander inductor

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A novel MEMS-based tunable meander inductor is reported. The inductor is fabricated using a single metal layer in a low-cost commercially available Metal-MUMPs™ process. The mutual inductance of the meander inductor is tuned by changing the gaps between the meander turns using a chevron-type thermal actuator. An air trench underneath the inductor has been made to reduce the loss in the silicon substrate and improve quality factor (Q -factor). Tuning range of $\sim 50.8\%$ and maximum Q -factor of 8.17 have been achieved at 5.79 GHz by stretching the meander inductor for 22 μm . The total footprint of the device is 0.58 mm^2 .

Introduction: Tunable circuits are the basic building blocks in radio-frequency (RF) tuning systems. Therefore, tunable inductors and capacitors are of great interest in the communications industry. Tunable inductors can provide the functionalities of accurate impedance matching and resonance frequency tuning. The magnetic material-based tuning inductor has been presented in [1]. The inductance can be tuned either by changing core permeability or by inserting the core in and out of solenoid inductors [2]. These inductors have limited Q -factor due to the losses in the magnetic core at high frequency. Several inductors are tuned by changing the mutual coupling through varying the distance between two inductors, as reported in [3, 4]. In some designs, switches have been used to select the turns to be activated in spiral inductors [5, 6]. These devices require high voltages, which are difficult to provide in system-on-chip applications. Many active CMOS tunable inductors are presented in [7–9]. Active CMOS tunable inductors have advantages over spiral inductors in terms of tunability, Q -factor, and area; however, they suffer from issues of noise and nonlinearity [10]. A high-performance tunable inductor has been fabricated using a piezoelectric actuator to change the gap between two coils [11]. However, hysteresis exists during sweeping up and down in actuation. Thermal actuators are suitable for low actuation voltage applications where power consumption is of less importance compared with voltage [12]. Tunable inductors with thermal actuation have been introduced in [13, 14], which require low voltages and produce large displacements for changing the gap between two inductors or changing the mutual coupling inside the inductor.

In this Letter, a design of MEMS-based tunable meander inductor with a single metal layer and thermal actuation is reported. Unlike [14], the ground–signal–ground (GSG) pads are equally spaced, which results in uniform wave propagation and accurate measurements [15]. A tuning range of $\sim 50.8\%$ and a maximum Q -factor of 8.17 have been achieved at 5.79 GHz.

Device design and fabrication: The tunable meander inductor has been designed with small spacing s and long length l to obtain high mutual inductance of the inductor [16], as shown in Fig. 1. The advantage of a meander inductor over a spiral inductor is that only a single metal layer is needed, making the fabrication process cost-effective and simple. The meander inductor is actuated through a chevron thermal actuator. By thermal actuation, the gaps between the meander turns are increased, which decreases the negative mutual inductance of the inductor, as shown in Fig. 2. Therefore, the total inductance of the inductor is increased. The mutual inductance of the two parallel and equal segments can be obtained from the following equation [15]:

$$M(l, s) = \pm \frac{\mu_0}{2\pi} l \left[\ln \left(\frac{l}{s} + \sqrt{1 + \left(\frac{l}{s} \right)^2} \right) - \sqrt{1 + \left(\frac{s}{l} \right)^2} + \frac{s}{l} \right] \quad (1)$$

where μ_0 is the permeability of free space, l is the length of the conductor and s is the gap between the conductors, which are illustrated in Fig. 3. It is noted from the above equation that the mutual inductance can be tuned by changing the spacing s between the inductor turns. Table 1 shows the optimised design parameters of the tunable inductor. The design is fabricated in a standard Metal-MUMPs™ process. The meander inductor and thermal actuator are made of nickel (Ni) with a 0.5 μm gold layer on top of the nickel. The thickness of the nickel layer is 20 μm . The mechanical connection and electrical isolation between tunable inductor and thermal actuator are achieved by a 700 nm silicon nitride (Si_3N_4) layer, as illustrated in Fig. 2.

Fig. 1 SEM images of tunable inductor showing thermal actuator and meander inductor. Equally spaced GSG pads are fabricated for accurate high-frequency measurement

Fig. 2 Schematic view of tunable inductor

a Meander structure before actuation
b Meander structure after actuation

Fig. 3 Schematic view of two parallel conductors with spacing s between each other and length l

Table 1: Design parameters and values for tunable inductor

	Parameter	Value
Inductor	width of inductor beams (μm)	8
	spacing between inductor beams (μm)	10
	length of inductor beams (μm)	480
	number of turns, N	3
	width of suspension beam (μm)	8
	length of suspension beam (μm)	1000
Actuator	number of Chevron actuator beams	5
	initial angle of the actuator beams ($^\circ$)	1.05
	length of actuator beams (μm)	1000
	device thickness (μm)	20.5
	air trench thickness (μm)	25

Experimental results and discussion: Fig. 4 shows the photographic image of the probe arrangement. The inductance and Q -factor were measured on a Cascade Microtech's high-frequency probe station using a Rohde and Schwarz 9 kHz to 6 GHz ZVL vector network analyser. The vector network analyser was initially calibrated by open, short, load, and through calibration using Agilent's on-wafer calibration tool for the impedance standard substrate. The impedance of the device was recorded from 500 MHz to 6 GHz and converted to inductance. Fig. 5 shows the measured inductance of the tunable inductor with different displacements of the thermal actuator. The total inductance of the inductor increases with the increase of displacement, which is due to a decrease of negative mutual inductance. Fig. 6 shows the measured quality factors of the tunable inductor with different displacements of the actuator. The Q -factor increases with the increase in displacement. This is due to the increase in inductance of the inductor after actuation. The maximum quality factor of 8.16 has been achieved at 5.79 GHz.

Fig. 4 Photograph of probe arrangement on tunable inductor

Fig. 5 Measured inductance values with different displacements

Fig. 6 Measured Q -factor with different displacements

Conclusions: A novel MEMS-based tunable meander inductor is proposed and characterised. Unlike tunable spiral inductors, the meander tunable inductor is implemented using a single metal layer, thereby reducing the fabrication complexity. The inductance is almost constant from 1.5 to 6 GHz frequency, which is suitable for LC resonator and other RF communication systems. The inductance and Q -factor increase

by increasing the gaps between the meander turns. A tuning range of 50.8% has been achieved at 5.79 GHz.

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