High-Q Solenoidal Inductive Elements

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***Abstract*— A solenoid-like magnetic-storage element embedded in high-resistivity silicon is presented that maintains well-defined signal and signal return-paths. By not being focused on creating a lumped inductor equivalent, the design space is opened up. At 5 GHz an effective inductance of 1.9 nH with a Q of 30 increasing to a 10.6 nH inductance with a Q of 11 were achieved.**

I. Introduction

Lumped RF inductors find application as RF blocks and in matching and filtering networks. With an RF block the intent is to present a high RF impedance to a circuit, often the drain or collector of a transistor, while still passing DC. An inductor is the simplest component that provides this function. However the design objective is not to create an ideal inductor, it is the presentation of a high RF impedance but a short circuit at DC. With matching and filter networks the intent is to create a network that alternately stores energy in electric form and in magnetic form. A combination of a capacitor and an appropriately-sized inductor achieves this as does a quarter-wavelength or half-wavelength long transmission line. Various hybrid combinations of transmission lines and lumped reactive elements also can achieve the function of alternatively storing electromagnetic energy in electric and magnetic forms. The intent in developing a component that stores energy predominantly in magnetic form should not be the creation of a component that approaches an ideal inductor. That is, the intent is to create a component that stores energy predominantly in magnetic form and with very low loss. A component that also stores energy in electric form is permissible in the context of filters and matching networks. In this paper we present a component generally called a solenoidal inductor that has very low loss.

The creation of RF inductors has received considerable attention over the last decade because of their smaller size relative to a distributed structure enabling size-effective RF integrated circuits. Lumped RF inductors suffer from relatively low Q compared to what can be achieved with lumped capacitors and distributed resonators. Spiral inductors, see Fig. 1, are the most common type used in RFICs and MMICs. Q's of less than 10 at frequency up to 5 GHz with inductance values of 1 to 10 nH have been achieved on the low-resistivity silicon common for RFICs [1], [2]. By comparison, microstrip transmission line resonators can achieve $Q's$ of 150 or so. A Q of 10 provides limited utility but there is usually little other choice and using an on-chip inductor for an RF block still achieves higher amplifier efficiencies than if alternative resistive biasing was used. Spiral inductors with Q's of up to 50 at 10 GHz have been achieved on high-resistivity substrates such as GaAs.

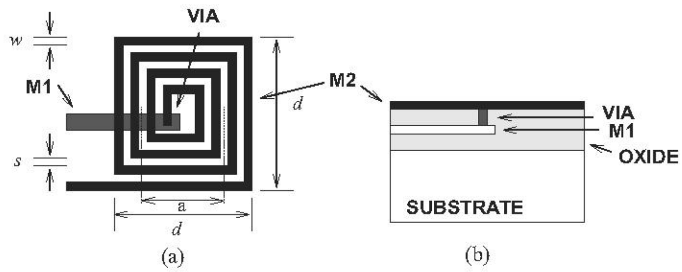

Fig. 1. A spiral inductor.

Silicon however remains the medium of choice for realizing integrated circuits and increasingly as an interposer in which silicon substrates are stacked with one or more active slices and others comprising passive elements and possibly micromachined cooling tubes. The performance of silicon-based inductors has been enhanced by implementing 3D structures such as toroids, Fig. 2, and solenoids, Fig. 3. Using micro-machining techniques the fields are kept away from the substrate by removing semiconductor material and forming "pop-up" shapes [3], [4], [5], [6], [7], [8]. Toroidal and solenoidal inductors achieve part of their performance by enhancing the flux coupling by directing the magnetic field through multiple loops.

Micromachining has been used to remove as much substrate in the vicinity of the spiral inductor. Solenoidal, see Fig. 3, and toroidal, Fig. 2, inductors have also been investigated with the Q's of toroids embedded in the bulk of around 20 at a few GHz [9]. At the input port of a toroid, see Fig. 2, the signal path and signal return path split and

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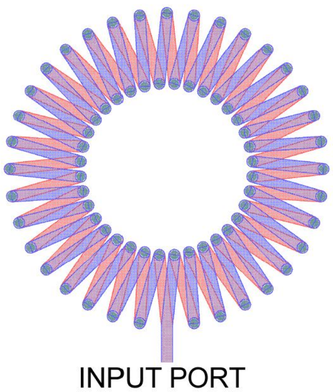

Fig. 2. A toroidal inductor.

TABLE I
MODEL PARAMETERS FOR THE SOLENOIDAL INDUCTORS SHOWN IN FIG. 3. THE TRANSMISSION LINES HAVE $Z_0 = 110\ \Omega$, AND $\ell = 10^\circ$ AT 10 GHZ.

Turns	Figure	L_L (nH)	R_L (Ω)	C_L (fF)	C_S (fF)	C_C (fF)
1	3(a)	0.35	0.4	40	35	65
2	3(b)	1.2	0.4	45	45	65
3	3(c)	1.9	0.5	55	55	85
4	3(d)	2.8	0.6	60	55	100
5	3(e)	3.8	0.7	60	58	110

follow different directions around the toroid. In practice this means that toroids are sensitive to nearby conductors. As such care must be used in using these devices.

The main intent of the work being pursued here is producing a layer of passives for a silicon-based 3D stack-up. As such pop-up structures are not suitable. However with an embedded passive layer without active devices a high-resistivity substrate can be used without limitation. Fortuitously, high-resistivity silicon substrates (10 kΩ-cm) are becoming increasingly available and affordable.

II. INDUCTIVE ELEMENT DESIGN

The direction taken in this work was to develop a magnetic energy storage element with well-defined signal return path as well as being embedded in the bulk. The structure developed is shown in Fig. 3 for solenoidal structures with one to five turns. The dimensions of the one-turn solenoid are shown in Fig. 4. The structure is effective at storing magnetic energy. The model of the solenoid is shown in Fig. 5 and the fitted parameters are given in Table I. An example of the fit obtained is shown in Fig. 6 for the 3-turn inductor.

It is not straightforward to determine the Q of the device presented here as magnetic energy is not stored in a single lumped component. Here the Q is calculated with the solenoid connected in a resonator with an ideal shunt capacitor C_R. In this configuration with Port 2 of

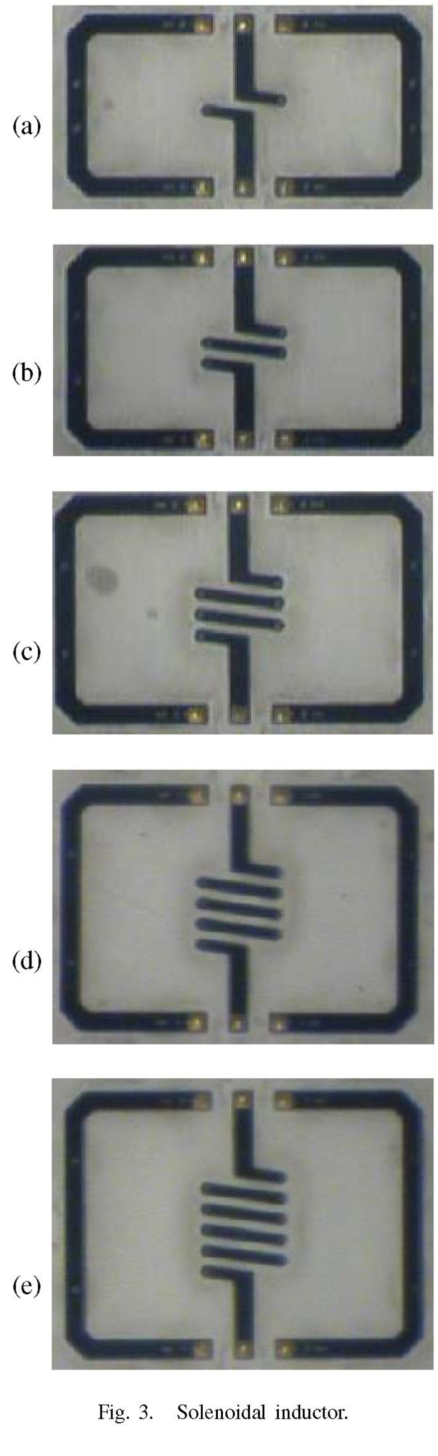

Fig. 3. Solenoidal inductor.

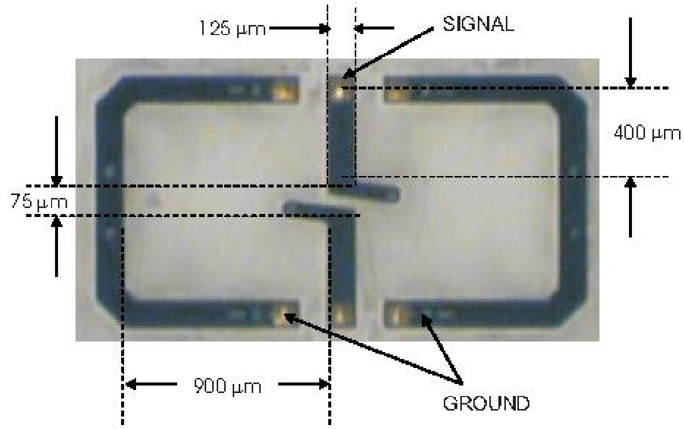

Fig. 4. Solenoid dimensions.

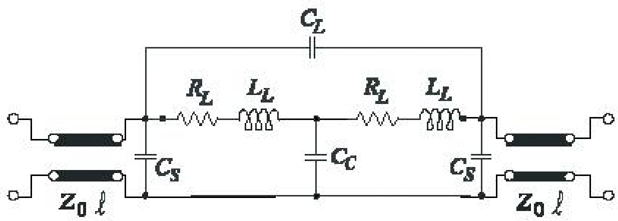

Fig. 5. Electrical model of a solenoidal inductor.

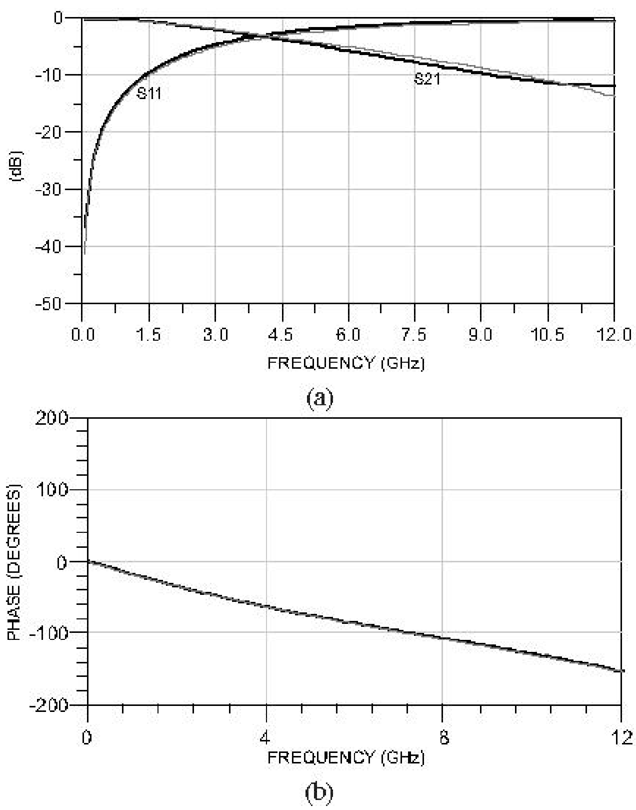

Fig. 6. Comparison of measurements and model for the three turn solenoidal inductor of Figure 3. (a) amplitude; and (b) phase.

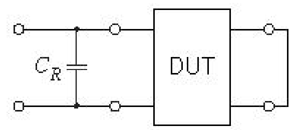

Fig. 7. Resonator structure for determining the Q of the device.

TABLE II
THE y_{11} PARAMETER OF THE DUT ALONG WITH EFFECTIVE INDUCTANCE VALUES.

Turns	1 GHz (mS)	5 GHz (mS)	10 GHz (mS)	L_{eff} (nH/Hz)
1	$95\angle -87.6°$	$17\angle -88.2°$	$4\angle 82.0°$	1.9 @5G
2	$53\angle -87.8°$	$7\angle -87.5°$	$4\angle 86.2°$	4.6 @5G
3	$35\angle -87.9°$	$3\angle -84.8°$	$8\angle 88.0°$	11 @5G
4	$25\angle -88.0°$	$2.6\angle -34.5°$	$12\angle 87.7°$	6.3 @1G
5	$19\angle -87.9°$	$1\angle 81.7°$	$20\angle 84.0°$	8.3 @1G

the DUT (or solenoid) shorted, the Q of the solenoid is

$$Q = \frac{\Im(1/y_{11})}{\Re(1/y_{11})} \tag{1}$$

where y_{11} is the port-based admittance parameter of the DUT. The extracted Q's of the solenoids are shown in Fig. 8. The peak Q is more than 20 over a substantial bandwidth. Selected y_{11} values are given in Table II as well as the effective inductance of the structure in the resonator configuration of Fig. 7.

III. Conclusion

An alternative magnetic-storage element was presented that is similar to a conventional solenoidal inductor. The element is designed to store magnetic energy while maintaining well-defined signal and signal return-paths. By not being focused on creating a lumped inductor equivalent, the design space was freed up considerably. An effective inductance of 1.9 nH with a Q of 30 was obtained at 5 GHz with a one-turn inductor occupying an area of 2 mm^2. However the area is not critical as the interposer layer with the inductor contains no active devices. Corresponding numbers for a two-turn inductance are 4.6 nH with a Q of 22; and for a three-turn inductor with a 10.6 nH inductance and a Q of 11. The inductive elements also can be viewed as slow-wave transmission lines.

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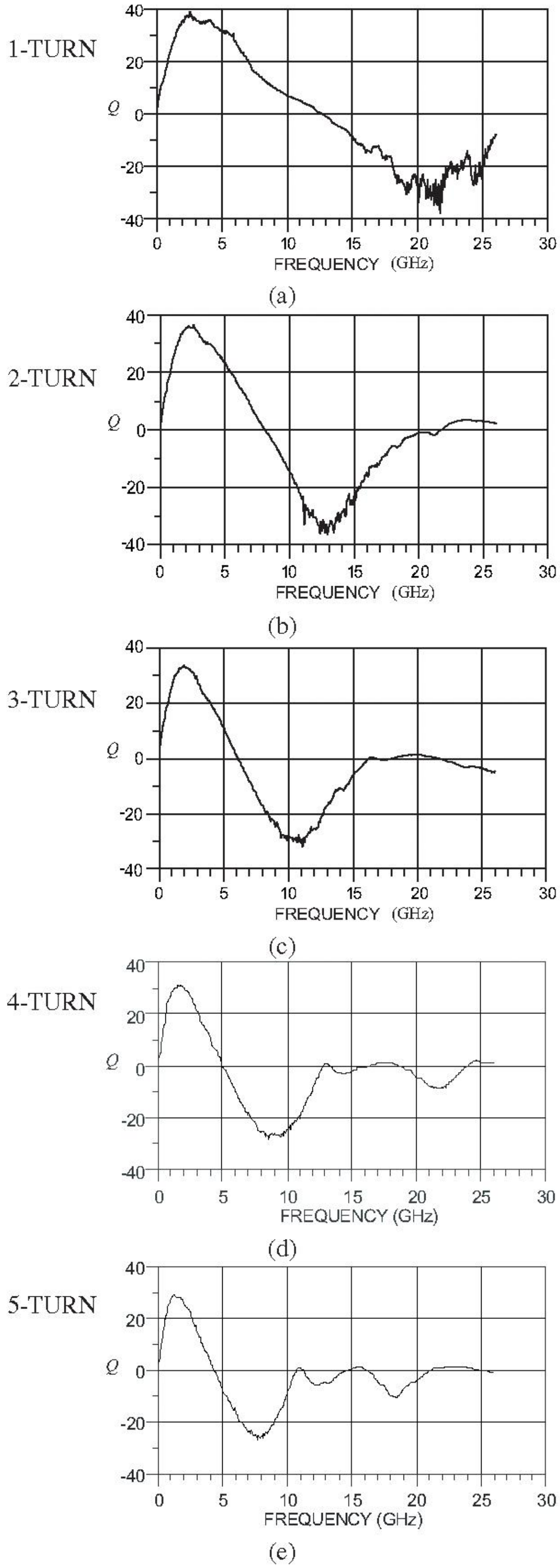

Fig. 8. Extracted Q of the solenoid inductors: (a) 1-turn; (b) 2-turn; and (c) 3-turn); (d)4-turn; (e) 5-turn.

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