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Design of T/R Switch Using LTCC Technology

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ABSTRACT

In this paper, a novel design of multilayer ceramic-based Transmit/Receive (T/R) switch using Low Temperature Co-fired Ceramic (LTCC) technology have been presented. Compact T/R switch has been designed by transforming quarter-wave transmission line to its lumped equivalent circuit. Especially, high-Q three dimensional inductors with double strip have been proposed and incorporated. The proposed inductor has been modeled by multi-conductor coupled lines. A measured inductor quality factor (Q) of 80 and a Self-Resonance Frequency (SRF) of 6.6 GHz have been demonstrated. The inductor library has been incorporated into the design of WCDMA T/R switch.

Key words : LTCC, High Q inductor, T/R switch, Double strip, Coupled line

1. Introduction

Recently, the handsets for mobile communications have been very popular and its miniaturization is strongly requested. Thus, several technologies have been developed to miniaturize RF and microwave components, circuits, and system.[1-3] Among them, Low Temperature Co-fired Ceramic (LTCC) technology provides the advantages which microwave devices such as filter, diplexer, antenna, etc., which are difficult to realize in a small size, can be size-reduced by fabrication in two- or multilayer configurations. Several kinds of multilayer microwave devices, such as filters, antenna, and balun, have been developed and each design methods and fabrication procedures have been reported.[4-7] Hence, they can be easily incorporated in the design of a variety of RF components such as RF switch, Voltage Controlled Oscillators(VCOs), Power Amplifiers(PAs), and mixers.

RF switch is one of the most important devices for TDMA based cellular phones, GSM handsets and wireless LANs. It is necessary that T/R switch is designed to reduce its size because a conventional T/R switch has a large size due to quarter-wave transmission line at Rx path.[8] The requirement can be obtained by designing T/R switch with lumped elements, such as inductor and capacitor.

In this paper, the development of high Q inductor incorporating a compact T/R switch and the design of a miniature T/R switch are reported. Modeling of high Q inductor and the design of multilayer ceramic-based T/R switch are performed by circuit simulator (HP-ADS). The properties of dielectric material have a dielectric constant of 7.8 and a loss tangent of 0.0015 at 10 MHz. Metallization can be silver for internal electrode or via-hole and silver-palladium alloy for solderable electrode.

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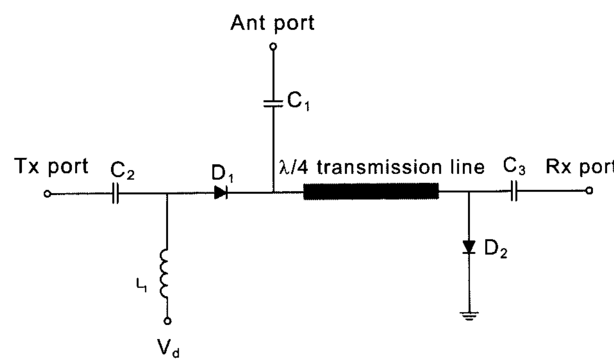

Fig. 1. Schematic of a conventional T/R switch with series diodes on the Tx port and shunt diodes on the Rx port.

2. Design of T/R Switch Using Lumped Equivalent Circuit

The schematic of a conventional T/R switch with quarter-wave transmission line is shown in Fig. 1. The basic circuit consists of a series PIN diode (D_1) on the Tx port and a shunt PIN diodes (D_2) on the Rx port. When T/R switch is designed with the quarter-wave transmission line at 2 GHz band, the overall size increases dramatically. To reduce the size of T/R switch, the lumped equivalent circuit shown in

Fig. 2 can be employed.

For WCDMA application, the equivalent circuit parameters of quarter-wave transmission line are as follows

$$L = \frac{Z_0}{\omega} sin\theta = 3.98 \text{ nH}$$

$$C = \frac{Y_0}{\omega} tan\frac{\theta}{2} = 1.6 \text{ pF}$$

($Z0=50\ \Omega$, $\theta=\beta l$)

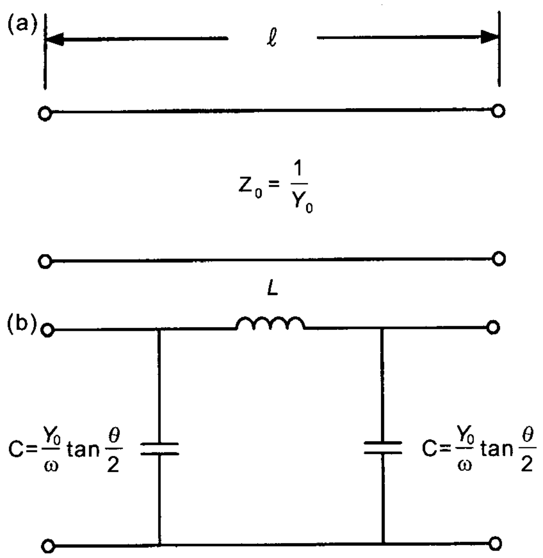

Fig. 2. Lumped equivalent circuit (b) of a quarter-wave transmission line (a).

3. Analysis and Modeling of 3D Rectangular Spiral Inductor

Fig. 3(a) and (b) shows the half- and three quarter turn inductors with a single strip, while Fig. 3(c) and (d) shows the proposed inductors to improve quality factor (Q) of 3D rectangular spiral inductor at 2 GHz band. The conventional and proposed inductors are designed with 3- and 6 conductor layers, and the line-width and thickness of electrodes have 0.2 mm and 10 μm, respectively. The inductors are implemented with the tapes, which have a dielectric constant of 7.8, tangent loss of 0.0015 at 10 MHz, and 96-μm-thick per one sheet. The LTCC inductor with multilayer configuration is designed based on 3D rectangular spiral structure, as shown in Fig. 3.

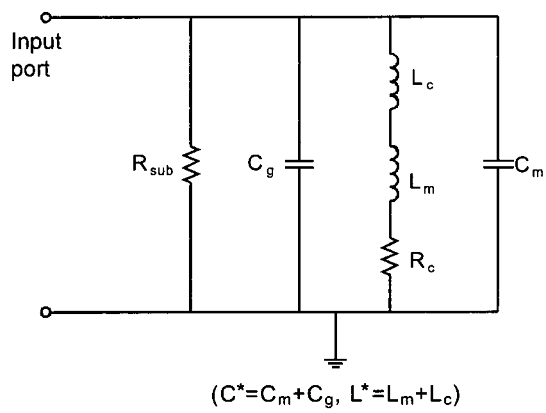

Fig. 4. One-port electrical model of LTCC inductor.

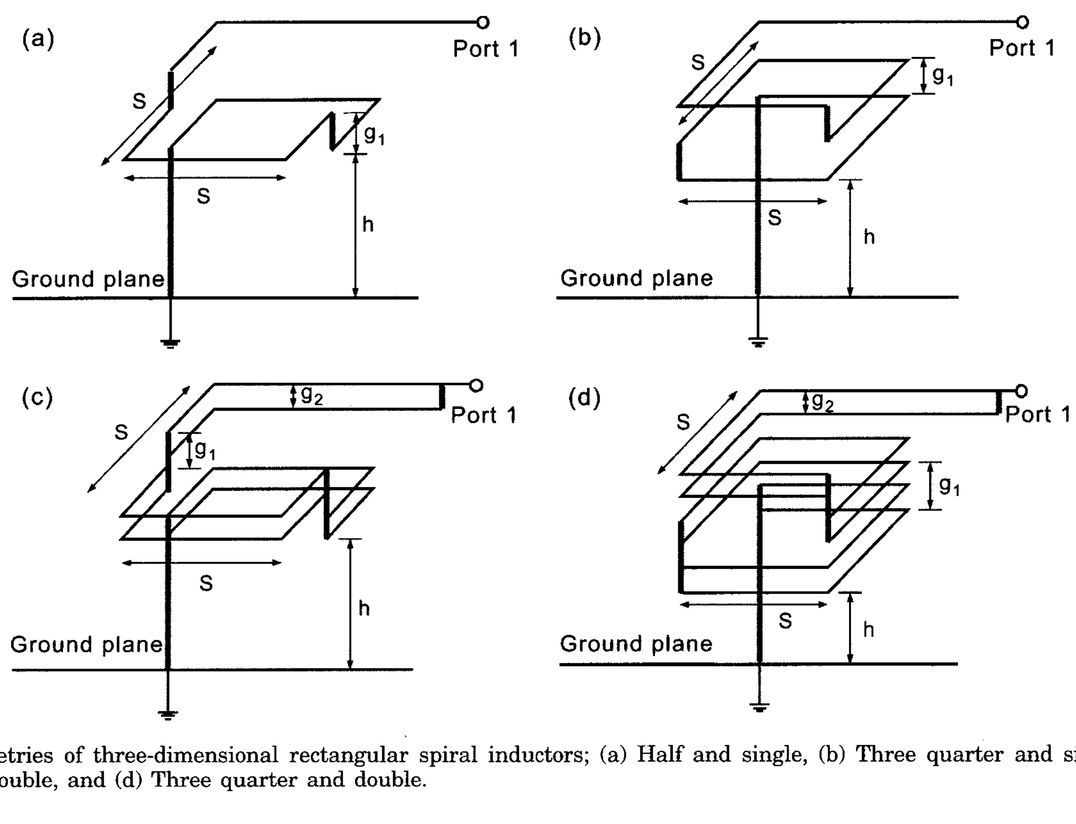

Fig. 3. Geometries of three-dimensional rectangular spiral inductors; (a) Half and single, (b) Three quarter and single, (c) Half and double, and (d) Three quarter and double.

One port electrical model suitable for the conventional and proposed inductor is shown in Fig. 4. L_C and L_m represent the self inductance and mutual inductance in 3D rectangular spiral inductor, and C_m and C_g represent the mutual capacitance between spiral turns and the capacitance between inductor footprint and ground plane, and R_C and R_{sub} represent the conductor loss of an inductor footprint and the dielectric loss by structural defects. Quality factor (Q), self-resonance frequency (f_{SRF}), and effective inductance (L_{eff}) of the electrical model shown in Fig. 4 are expressed as

$$Q = \frac{\omega L^*}{R_C}\left(1-\Delta R\left(\omega^2 L^* C^* + \frac{R_C C^*}{\omega L^*}\right)\right) \quad (1)$$

$$F_{SRF} = \frac{1}{2\pi\sqrt{L^* C^*}}\sqrt{\left(1-\frac{R_C{}^2 C^*}{L^*}+\frac{R_C}{R_{sub}}\right)} \quad (2)$$

$$L_{eff} = \frac{L^*(R_C/R_{sub}+1-\omega^2 L^* C^*)-R_C^2 C^*}{(R_C/R_{sub}+1-\omega^2 L^* C^*)^2+(\omega R_C C^*)^2}$$

$$\left(\Delta R = \frac{R_{sub}}{R_{sub}+R_C}\right) \quad (3)$$

ΔR in Eqn. (1) is a primary factor determining the location of Q_{max}. For simple expression, provided that $R_{sub} >> R_C$, R_C/R_{sub} is close to zero.

$$F_{SRF} = \frac{1}{2\pi\sqrt{L^* C^*}}\sqrt{\left(1-\frac{R_C{}^2 C^*}{L^*}\right)} \quad (4)$$

$$L_{eff} = \frac{L^*(1-\omega^2 L^* C^*)-R_C^2 C^*}{(1-\omega^2 L^* C^*)^2+(\omega R_C C^*)^2} \quad (5)$$

As shown in Eqn. (4) and Eqn. (5), the properties of SRF and effective inductance are mainly influenced by L^* and C^*, while Rsub has an effect on only quality factor Q.

The quality factor Q and effective inductance L_{eff} tend to changes largely by parasitic capacitors such as C_g and C_m of the electrical model in Fig. 4. Accordingly, the inductive structure is designed to suppress these parasitic capacitors in order to improve the inherent properties of the inductor such as L_{eff} and Q. However, the proposed inductive structure is designed to improve Q by reducing R_C and increasing L_m.

Fig. 5 shows the measured results of the 3D rectangular spiral inductors with ground planes 6 layers apart (*h* in Fig. 3). The measurement is performed by a probe station and network analyzer. Inductors with double strip have a higher than those with single strip by decreasing R_C and increasing L_m. However, the SRF of the proposed inductors decreases

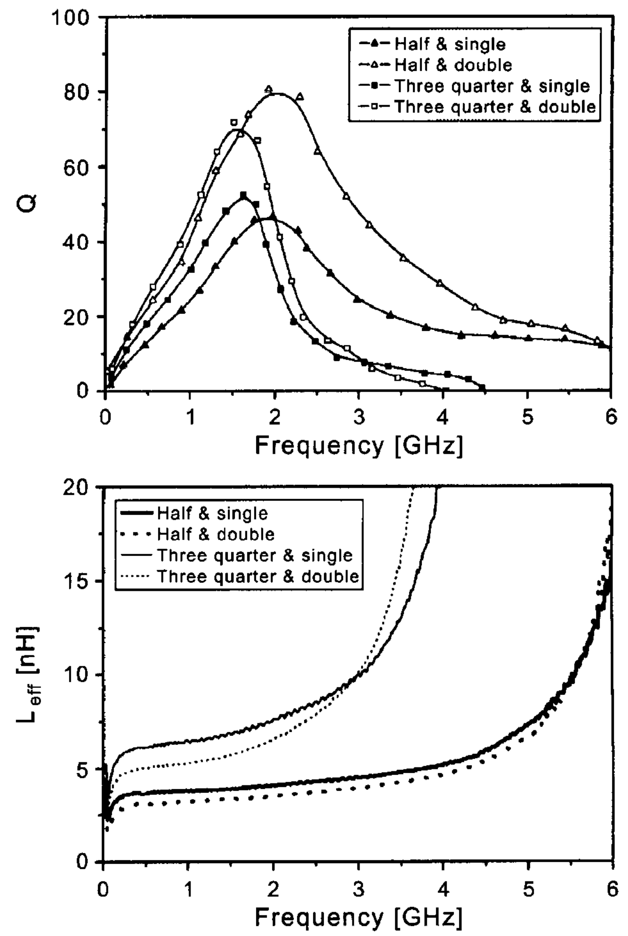

Fig. 5. The measured results of 3D rectangular spiral inductors (W= 0.2 mm, *S*=1.0 mm, g_1= $2g_2$= 2 layer).

Table 1. Equivalent Model Parameters of the Measured Results

	Inductor (a)	Inductor (b)	Inductor (c)	Inductor (d)
L* [nH]	3.86	3.2	5.9	5.15
C* [pF]	0.13	0.18	0.21	0.29
R_C [Ω]	0.53	0.25	0.65	0.35
R_{sub} [kΩ]	5	5	8	10

Table 2. The Measured Results of 3D Rectangular Spiral Inductors

		Inductor (a)	Indutor (b)	Inductor (c)	Inductor (d)
SRF [GHz]		–	–	4.5	4.1
Q_{max}		46.6 (1.97 GHz)	80.5 (1.91 GHz)	52.5 (1.62 GHz)	71.9 (1.50 GHz)
L_{eff} [nH]	1 [GHz]	3.94	3.27	6.20	5.45
	2 [GHz]	4.19	3.52	7.33	6.74
	3 [GHz]	4.69	4.02	10.52	10.96

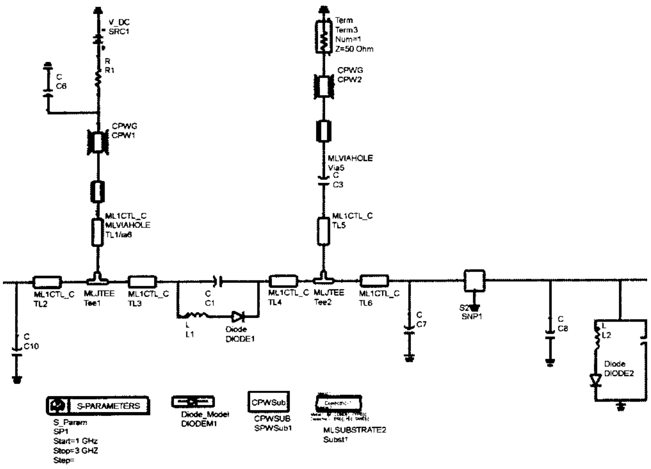

Fig. 6. T/R switch circuit schematic with lumped equivalent circuit.

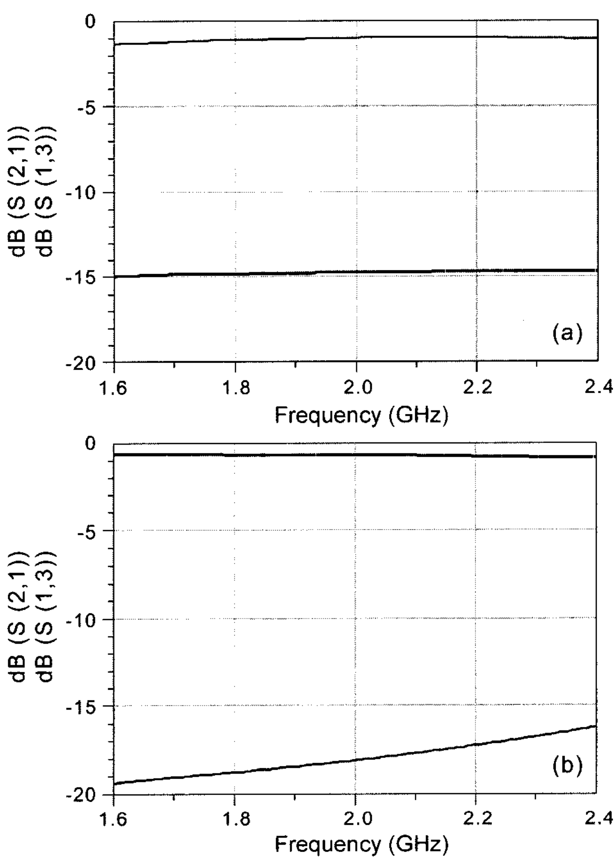

Fig. 7. The simulated results of T/R switch; (a) Transmit mode and (b) Receive mode.

and L_{eff} changes abruptly in the function of frequency due to increase of coupling capacitance C^*. Table 1 shows the equivalent parameters of the measured results in Fig. 5. As indicated in Table 2, the half-turn inductor with double strip exhibits L_{eff} of 3.52 nH with the Q of 80 at 2.0 GHz and the three quarter-turn inductor with double strip exhibits L_{eff} of 5.75 nH with the Q of 71.9 at 1.5 GHz, respectively.

4. Simulations and Results

The schematic of a T/R switch design with lumped equivalent circuit is shown in Fig. 6. The T/R switch is designed with PIN diode (HVD142, Hitachi) to be applied to WCDMA. When the shunt diode toward Rx port is "ON", it presents a very high impedance state from antenna port or Tx to Rx. Thus, all the RF signals coming from Tx will arrive to the antenna port with minimum leakage to Rx. When control voltage is zero, two diodes are in "OFF" state. On the Tx side, the RF signal will see an open circuit since the series PIN diodes are in "OFF" state. Thus, the majority of the RF signal arrives at the Rx port with minimum leakage to Tx port. Fig. 7 shows the simulated results of the T/R with lumped equivalent circuit. At transmit mode, a minimum insertion loss is -1.2 dB in the frequency range of 1920-1980 MHz. At receive mode, a minimum insertion loss is -0.8 dB in the frequency range of 2110-2170 MHz

5. Conclusions

In this paper, the design of multilayer ceramic-based T/R switch and high-Q 3D inductor with double strip for incorporating the T/R switch have been presented. 3D rectangular spiral inductors have been analyzed and modeled by one-port equivalent circuit, which has lumped parameters compatible with physical phenomena. The half-turn inductor with double strip show a Q performance as high as 80 at 2.0 GHz for 3.52 nH and the three quarter-turn inductor with double strip exhibits Leff of 5.75 nH with the Q of 71.9 at 1.5 GHz. The results have overcome the Q-limitation typically encountered for on-chip passive. The inductors have been incorporated into the T/R switch with LTCC passives exhibiting minimum insertion loss of -1.2 dB at Tx mode and -0.8 dB at Rx mode.

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