Tunable Active Filters Having Multilayer Structure Using LTCC

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***Abstract*—Two types of tunable filters have been developed at 400- and 800-MHz frequency bands, respectively. These filters have been fabricated with low-temperature co-fired-ceramics multilayer technologies assisted by varactor diodes. The filter size is 5.6 × 5.6 × 3.0 mm. Each filter has approximately 11% and 13% tuning range of frequency with a controlling voltage of 1–4 V, IL < 2.0 dB, and has an attenuation over 40 dB at $fo \pm 30\%$, respectively. Temperature stability data is also discussed.**

***Index Terms*—Ceramics, multilayers, tunable filters, varactors.**

I. Introduction

TUNABLE devices are widely applied in modern radio system. For example, voltage-controlled oscillators (VCOs) are very common in mobile radio systems such as a cellular phone, two-way radio, etc. In general, fixed filters such as a dielectric resonator filter, surface acoustic wave (SAW) filter, and multilayer ceramic filter are used as a microwave filter in such a mobile radio system. Recently, many mobile systems have been developed. As a result, the demands for a filter having wide bandwidth and sharp attenuation performance have rapidly increased. Filters having many poles are designed to achieve such demands. This increases the difficulties of design and mass production of microwave filters. Tunable filters are known to be effective to solve these problems.

In some applications, it is required for microwave filters to tune their pass frequency band [1], [2]. Automatic tuning is preferable because the manual tuning procedure needs skill and know-how according to microwave filter technology. Usually, the manual tuning procedure causes higher cost, lower productivity, and becomes a bottleneck in mass production. It is also known that automatic tunability of a selective channel might attain a weakened specification of a filter compared with a fixed filter.

Low-temperature co-fired-ceramic (LTCC) technology is well known to be suitable to build a multilayer structure in which many passives are able to be embedded [3]. The LTCC process utilizes high-conductivity metal, such as pure silver for inner conductor material, and brings the benefit of low loss in microwave application. LTCC is applied in many electronic components and modules such as filters, baluns, automotive engine control modules, motherboards for super computer, etc.

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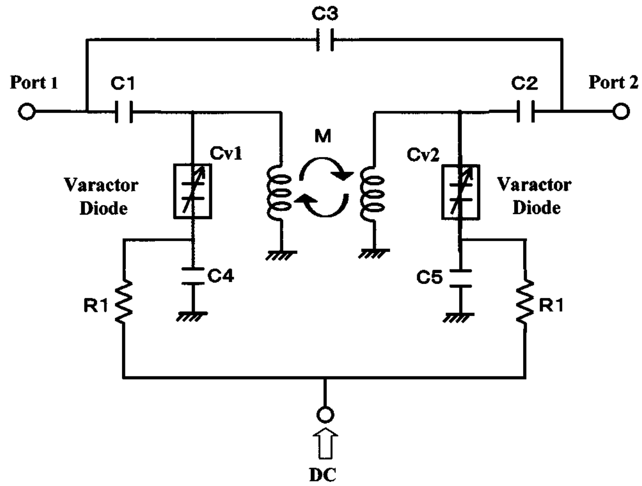


Fig. 1. Circuit configuration of the tunable filter.

TABLE I
DESIGN PARAMETERS OF TUNABLE FILTERS

	C1, C2 (pF)	C3 (pF)	C4, C5 (pF)	Cv1 – Cv2 (pF)	L1, L2 (nH)	Coupling Coefficient	R1, R2 (ohm)
400MHz	3.1	0.28	27.5	10.0-18.0	11.0	0.1	>10000
800MHz	1.0	0.02	15.0	2.0-4.0	7.9	0.1	>10000

In this paper, the tunable microwave filters at 400 and 800 MHz are described. The tunable filters have a multilayer structure in which over ten passives are embedded with LTCC technology and have a compact size, i.e., 5.6 × 5.6 × 2.4 mm. The tunability is attained with the help of varactor diodes. It is usually known that varactor diodes suffer from a decrease of an unloaded quality factor with an increase of microwave frequency. To avoid this decrease of the quality factor, RF circuits have been adjusted to achieve low loss at microwave frequency. Transmission properties and temperature properties are presented.

II. Design and Fabrication

A fundamental equivalent circuit of tunable filters is shown in Fig. 1 and Table I. The passband frequencies are designed as 400 and 800 MHz, respectively. These filters are implemented in a three-dimensional lumped-element topology having two-pole bandpass response with both sides notched. All passive components, except for resistors, are designed to be embedded in the LTCC substrates.

Though an actual embedded component has a three-dimensional structure, it brings frequency response of electrical property for each component. Fig. 2 shows a practical three-dimen-

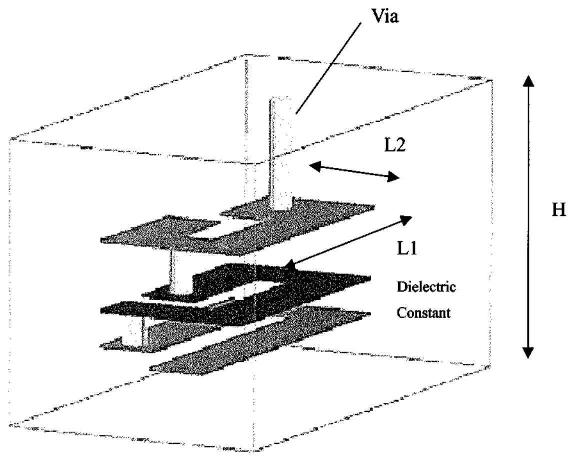


Fig. 2. Structure model of a helical inductor.

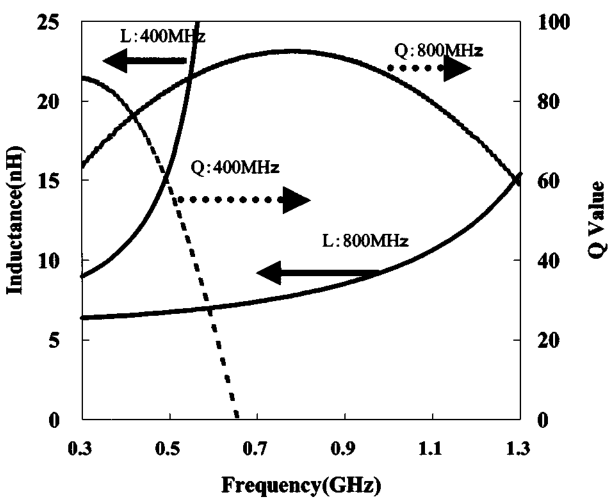


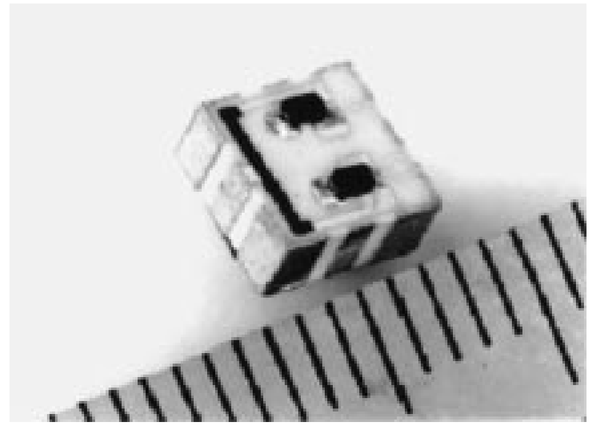
Fig. 3. Frequency responses of helical inductance. 400 MHz: dielectric constant: 75, H: 2.2 mm, $L1$: 2.6 mm, $L2$: 2.6 mm. 800 MHz: dielectric constant: 7.7, H: 1.8 mm, $L1$: 3.0 mm, $L2$: 2.0 mm.

TABLE II
DIELECTRIC CHARACTERISTICS OF LTCC MATERIALS

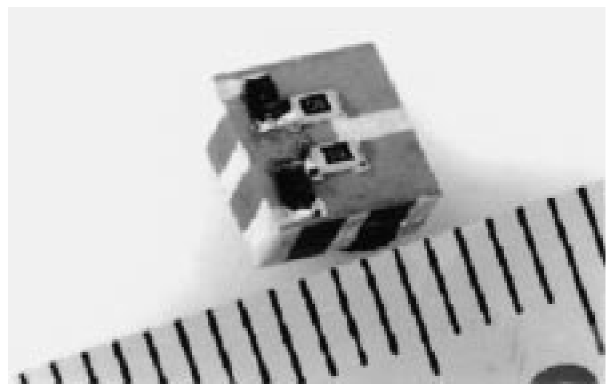
Material	Dielectric Constant	Q·f (GHz)	Tcf (ppm/°C)
CaO-Al_2O_3-SiO_2-B_2O_3 [3]	7.7	2000	-35
BaO-Nd_2O_3-TiO_2-SiO_2-B_2O_3 [4]	75	2500	10

sional structure of a helical inductor. Simulated frequency responses of the helical inductor are shown in Fig. 3. Inductance increases according to an increase of frequency. In a practical structure, it is important to choose the structure in which inductance increases slowly at the application frequency. As for the Q of the inductance, it has a maximum point according to an increase of frequency. An appropriate structure must be chosen to attain low loss.

Performances of these tunable filters are simulated using the finite-element method. Filters are fabricated by an ordinary LTCC process. The substrate materials are BaO–TiO_2–Nd_2O_3–SiO_2–B_2O_3 for 400 MHz and



(a)



(b)

Fig. 4. Photographs of mutilayer tunable filters. (a) 410–470-MHz tuning range with 1.2–3.7 V. (b) 780–870-MHz tuning range with 2.0–4.0 V.

CaO–Al_2O_3–SiO_2–B_2O_3 for 800 MHz, respectively [3], [4]. Dielectric characteristics of them are summarized in Table II.

These LTCC materials are sheet-casted to 0.07- and 0.1–mm-thick tape. Electrode patterns are formed by a screen-printing method. Pure silver is applied to both internal and external electrodes. RuO_2 resistors are printed on the surface to apply dc voltage to varactors for an 800-MHz filter contrary to the chip resistor mounted for a 400-MHz filter. After stacking the printed sheets, the stacked blank is cut into pieces, and then co-fired in the furnace around 900 °C for 1 h in air. Varactors (Toshiba, 1SV305 for 400 MHz, 1SV285 for 800 MHz) are mounted on the top surface to control passband frequency with dc voltage. Temperature properties of tunable filters are measured after 1 h, soaking in the oven in which temperature changes from -20 to $+80$ °C. Temperature coefficient of frequency (Tcf) of the tunable filter is calculated by the following equation:

$$\mathrm{Tcf} = (f_{-20} - f_{+80})/-100 f_{+25} \tag{1}$$

where f_T is the center frequency of 3-dB bandwidth at T °C.

III. DESIGN AND FABRICATION

Fig. 4(a) and (b) presents photographs of the tunable filters. The overall sizes of both filters are 5.6 mm × 5.6 mm × 3.0 mm (5.6 mm × 5.6 mm × 2.4 mm excluding the varactor height). The differences in the outside color are derived from LTCC material. CaO–Al_2O_3–SiO_2–B_2O_3 is white after sintering

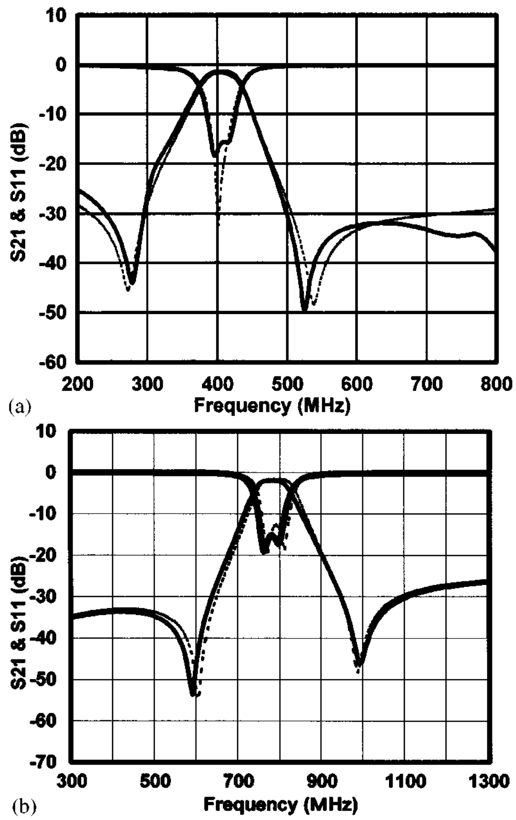


Fig. 5. Measured response and simulation results. (a) 400-MHz filter (1.2 V). (b) 800-MHz filter (2.0 V). Measured (—). Simulation (- - -).

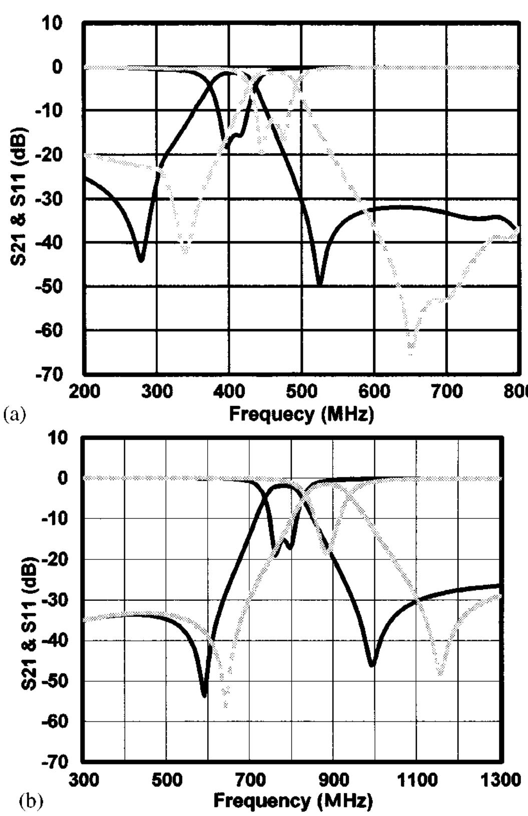


Fig. 6. Measured response of tunability. (a) 400-MHz filter: 1.2 V (—), 3.7 V (- - -). (b) 800-MHz filter: 2.0 V (—), 4.0 V (- - -).

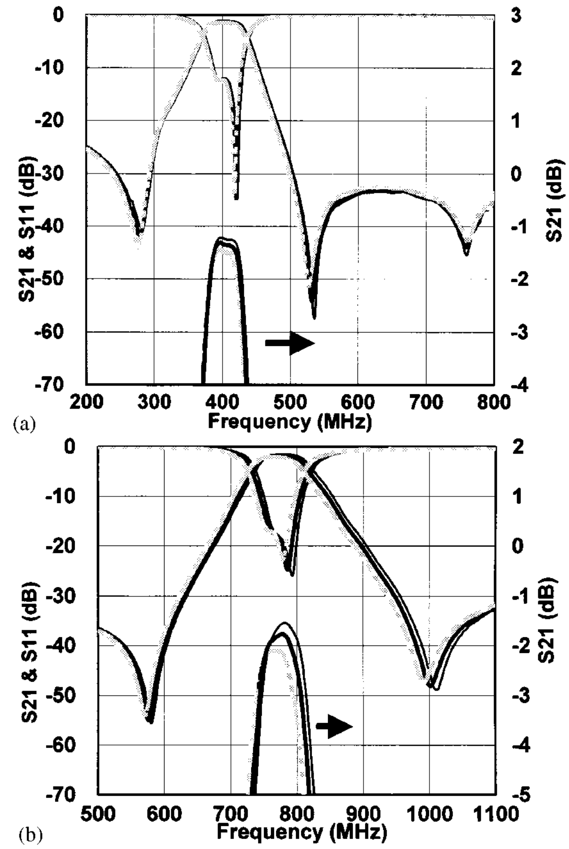


Fig. 7. Measured responses versus temperature. (a) 400-MHz filter (1.2 V). (b) 800-MHz filter (2.0 V). -20 °C (—). $+25$ °C (- - -). $+80$ °C **(—)**.

TABLE III
MEASURED PERFORMANCE OF TUNABLE FILTERS

Tunable Filter	Tunable frequency (MHz)	Tuning Voltage (V)	Band Width (MHz)	Insertion Loss (dB)	Attenuation at fo+-30% (dB)	Tcf (ppm/deg-C)
400MHz	410-470	1.2-3.7	66	1.4	>40	-98.7
800MHz	780-870	2.0-4.0	82	1.8	>40	-154.8

[see Fig. 4(a)] contrary to the green color [see Fig. 4(b)] of $BaO–TiO_2–Nd_2O_3–SiO_2–B_2O_3$.

The measured transmission data of actual filters are shown in Fig. 5 superimposed with the electromagnetic simulation results. Good co-relationships are confirmed between the measured data and simulation results. Excellent performances of both filters for practical use also confirm that insertion losses are less than 2.0 dB, and attenuation on both sides of the passband at $fo \pm 30\%$ are over 40 dB, respectively.

Fig. 6 shows the measured data of tunability according to the applied voltage to varactor diodes. The 400-MHz filter is tuned from 410 to 470 MHz with a tuning voltage of 1.2–3.7 V. The 800-MHz filter is tuned from 780 to 870 MHz with a tuning voltage of 2–4 V.

Temperature characteristics are summarized in Fig. 7. The temperature coefficient of the resonant frequency for a 400-MHz filter has been found to be stable as -98.7 ppm/°C contrary to that of the 800-MHz filter, as -154.8 ppm/°C. Performances of the tunable filter are summarized in Table III. Tcf of the varactor diode is $+7.0\%$ and $+5.5\%$ at the measured voltage for the 400- and 800-MHz filters, respectively.

A small temperature coefficient of resonant frequency of $BaO–TiO_2–Nd_2O_3–SiO_2–B_2O_3$ contributes good temperature stability of the 400-MHz filter. Though the 800-MHz filter has a larger temperature coefficient than the 400-MHz filter, it is enough to be used in a practical sense if the bandwidth is large enough to channel width since this filter is tuned to each frequency channel.

IV. Conclusions

Practical tunable filters have been developed at 400- and 800-MHz frequency bands, respectively. These filters have multilayer structures and have been fabricated with LTCC technology. $CaO–Al_2O_3–SiO_2–B_2O_3$ and $BaO–Nd_2O_3–TiO_2–SiO_2–B_2O_3$ are applied as LTCC materials for the 400- and 800-MHz filters, respectively. The performance of these filters have been confirmed to have excellent properties for practical use, i.e., insertion losses are less than 2.0 dB at room temperature, and attenuations on both sides of the passband are over 40 dB. Temperature stability has been found to be enough for practical use.

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