유도결합구조 가변형 대역통과필터의 이론적 분석 및 모델링

이태창, 박재영
마이크로/나노 소자 및 패키징 연구실, 전자공학과 광운대학교, 서울

Theoretical Analysis and Modeling for PCB Embedded Tunable Filter with Inductive Coupling

Tae C. Lee and Jae Y. Park
Micro/Nano Devices & Packaging Lab. Department of Electronic Engineering, Kwangwoon University, Seoul

Abstract – Fully embedded tunable bandpass filter (BPF) with inductive coupling circuits is newly designed and demonstrated for UHF TV tuner ranged from 500MHz to 900MHz receivers. Conventional RF tuning circuit with an electromagnetic coupled tunable filter has several problems such as large size, high volume, and high cost, since the electromagnetic coupled filter is comprised of several passive components and air core inductors to be assembled and controlled manually. To address these obstacles, compact tunable filter with inductive coupling circuit was embedded into low cost organic package substrate. The embedded filter was optimally designed to have high performance by using high Q spiral stacked inductors, high dielectric $BaTiO_3$ composite MIM capacitors, varactor diodes. It exhibited low insertion loss of approximately -2dB, high return loss of below -10dB, and large tuning range of 56.3%. It has an extremely compact size of 3.4 x 4.4 x 0.5mm^3.

1. Introduction

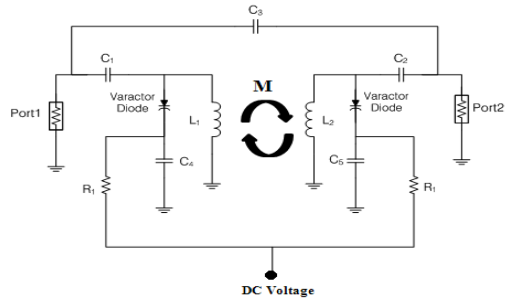
Recently, much research efforts have been performed to develop small and tunable devices for intelligent microwave systems such as communications, radars, and test equipments. In particular, in order to reduce their sizes, tremendous efforts have been performed by utilizing various resonant structures [1], geometry configurations [2-3], coupling structures [4], and coupling method [5].

In this paper, detailed theoretical and experimental analysis of the compact PCB embedded tunable filter are performed and compact inductive coupled UHF filters are designed by using peaking inductor (L_m) instead of mutual inductance of the loop gap resonator and magnetic coupling commonly used. The optimally designed filters are fabricated by embedding them into multi-layered organic package substrate instead of LTCC substrate. For extremely miniaturizing the designed tunable filter, embedded high Q stacked spiral inductors and high dielectric $BaTiO_3$ composite MIM capacitors are applied. The tunable filter is designed for operating at frequencies ranged from 500MHz to 900MHz. The tunability is obtained by using varactor diodes.

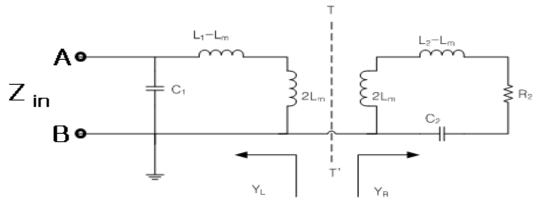
2. Theoretical Analysis and Fabrication

2.1 Foundation of Bandwidth Tuning Method

The proposed tunable filter was designed with inductive coupling circuit to be embedded into the multi-layered organic package substrate. Fig. 1 shows a circuit diagram of conventional microwave tunable filter with magnetic coupling like a TV tuner that is comprised of two LC resonant circuits. There are some drawbacks commonly occurred in the conventional tunable filter such as large size/volume, difficulty in tuning, and manual assembly. In order to address these problems, the proposed tunable filter is modified, optimized, and implemented.



<Fig. 1> Circuit configuration of conventional tunable filter with magnetic coupling



<Fig. 2> A lumped-element circuit model of asynchronously tuned LC resonator coupled magnetically

Fig. 2 shows a lumped-element circuit model of asynchronously tuned LC resonators that are coupled magnetically, denoted by L_m instead of mutual inductance M.

To allocate the resonant frequency from 500MHz to 900MHz, the components values L_1, L_2, C_1, and C_2 are obtained by using analog circuit simulation. These two resonant frequencies of the uncoupled resonators are given as follows

$$\omega_{01} = (L_1 C_1)^{-1/2}, \omega_{02} = (L_2 C_2)^{-1/2} \tag{1}$$

The designed values are about 8.6nH (L_1, L_2) and 15pF(C_1, C_2) to set the starting resonant frequency, 500MHz. The condition for natural resonance of the coupled resonant circuit is follows

$$Y_L = -Y_R \tag{2}$$

Where Y_L and Y_R are the pair of admittances looked into the left and the right of reference plane T-T' in Fig. 2. This resonant condition leads to

$$\frac{1}{j\omega L_m} + \frac{j\omega C_1}{1-\omega^2 C_1 (L_1 - L_m)} + \frac{j\omega C_2}{1-\omega^2 C_2 (L_2 - L_m)} = 0 \tag{3}$$

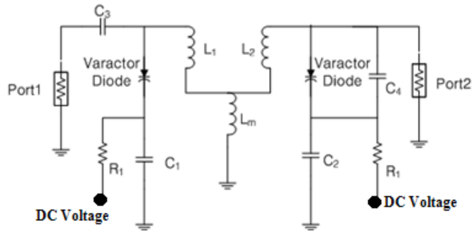
The eigen-equation in the equation (3) can be expanded as

$$\omega^4 (L_1 L_2 C_1 C_2 - C_1 C_2 L_m^2) - \omega^2 (L_1 C_1 + L_2 C_2) + 1 = 0 \tag{4}$$

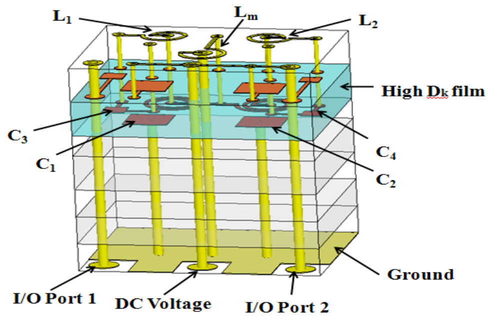
Similarly, this bi-quadratic equation has four eigen-values, and the two positive real values of interest are given as follows

$$\omega_{h,l} = \sqrt{\frac{(L_1 C_1 + L_2 C_2) \pm \sqrt{(L_1 C_1 - L_2 C_2)^2 + 4 C_1 C_2 L_m^2}}{2(L_1 L_2 C_1 C_2 - C_1 C_2 L_m^2)}} \tag{5}$$

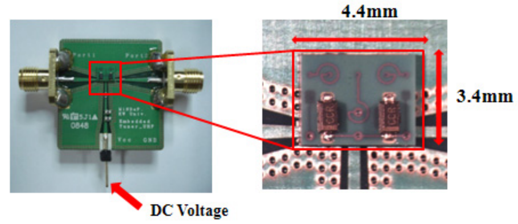
From the equation (5), two resonant frequencies can be found.



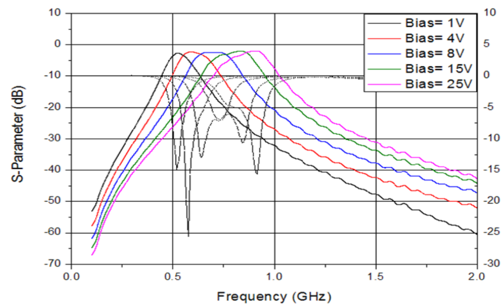
<Fig. 3> Proposed tunable filter circuit



<Fig. 4> 3D structural geometry of an embedded tunable filter.



<Fig. 5> Photographs of tunable filter embedded into 8-layered organic package substrate.



<Fig. 6> Measured S-parameters of fabricated tunable filter. Insertion loss (S21), return loss (S11). Bias voltages are varied from 1.0V to 25.0V.

2.2 Fabrication of PCB Embedded Tunable Filter

Fig. 3 shows a lumped-element circuit model of Proposed tunable filter circuit with a peaking inductor (L_m). The role of peaking inductor (L_m) determines a coherence from L_1 to L_2. Fig. 4 shows 3D structural geometry of proposed tunable filter. The proposed package substrate is comprised of a prepreg (PP, 1^{st}, 3^{rd}, 6^{th}, 7^{th}, 8^{th} layer), high D_k film, resin coated copper(CCL, 4^{th} ,5^{th} layer). The PP ,CCL and High D_k RCC materials have relative dielectric constant of 4.1, 4.1, 18 and loss tangent of 0.015, 0.015, 0.008, respectively.

The fabricated tunable filter has a size of 3.4mm x 4.4mm x 0.5mm which was extremely miniaturized in comparison of conventional RF tuning circuit for TV tuner. Fig. 5 shows photograph of the fully embedded tunable filter into a multi-layered PCB package substrate.

3. Experimental results

The fabricated tunable filter has been measured and characterized by using an Agilent 8753ES network analyzer. The measured frequencies are ranged from 0.1GHz to 2GHz for commercial RF applications.

Fig. 6 shows the frequency response of the fabricated tunable filter as the bias voltage on the varactors is varied from 1.0V to 25.0V. As shown in Fig.4, the center frequency starts at 518MHz at 1.0V with insertion loss of 2.45dB and return loss of 14.05dB. At 25.0V, the center frequency, insertion loss, and return loss are shifted up to 917MHz, 1.83dB, and 15.36dB, respectively. Total tuning range of 56.3 percent is achieved. 3-dB bandwidth of the tunable filter has about 20 percent which are 105MHz at the lowest frequency and 181MHz at the highest frequency.

4. Conclusion

Compact PCB embedded tunable filters have been designed, fabricated, characterized, and compared by using PCB embedded high Q stacked spiral inductors and high dielectric $BaTiO_3$ composite MIM capacitors. The performance characteristics of the fabricated filters were strongly related with the coupling coefficient which was determined by the mutual inductance and self inductances of the inductors used in the designed filter circuit. The measured performance characteristics were agreed with the 3D EM simulated ones. Since their sizes and volumes are much smaller than the conventional ones reported, they can be directly utilized for advanced TV tuner. The proposed design and fabrication technology are also promising for advanced organic based products with various functionalities, low cost, small size and volume.

5. Acknowledgment

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