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Miniaturized Bandpass Filter with Controllable Transmission Zero using Low-Temperature Co-fired Ceramic (LTCC) Technology

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The trend toward miniaturization of satellite payloads necessitates the development of increasingly smaller and more efficient receiver and transmitter systems. Consequently, the components that make up these receivers and transmitters must be compact and utilize multi-layer technology to create hybrid architectures. Microstrip-based high-rejection filters necessitate a significant amount of space, which hinders the implementation of radio frequency systems in package (SiPs). The objective of this study is to develop compact filters for satellite receivers. This research focuses on constructing a filter that has improved selectivity to reject unwanted image frequencies while keeping the filter order the same. A third-order grounded combline resonator loaded with a capacitor has been chosen as the fundamental configuration for the proposed bandpass filter design. The paper introduces a new method to improve the selectivity of the combline resonator bandpass filter by incorporating a transmission zero, which is achieved by introducing a U-shaped coupling structure between non-adjacent resonators in a separate layer. The position of the transmission zero can be accurately controlled by adjusting the length of the U-shaped coupling transmission line. An additional coupling pad has been inserted between the resonator and the U-shaped pattern on a separate layer to guarantee the coupling between the resonators and adjust the bandwidth. An innovative method was employed to build and simulate a filter for the Ku-band frequency range of 12.7 GHz to 13.0 GHz. The filter has a 1-dB absolute bandwidth of 310 MHz and achieves a rejection of 26 dB at 11.6 GHz, the image frequency for a standard payload receiver. The filter's dimensions are 6.5 mm × 2.58 mm × 0.89 mm, making it an essential component of the RF SiP.

Keywords: Coupling-coefficient, Cross-coupling, Hybrid structures, LTCC technology, Resonator

Introduction

Low-Temperature Co-fired Ceramic (LTCC) is a technology used to manufacture multilayer circuits from ceramic substrates utilized in manufacturing components operating at radio frequency (RF) and microwave frequencies. A typical LTCC device consists of multiple dielectric layers, screen-printed low-loss conductors, embedded baluns, resistors & capacitors and via-holes for interconnecting the multiple layers. LTCC devices are produced by applying the conductive, resistive metal paste on each ceramic substrate sheet as needed and then pressed together in a specific sequence, laminating them together. Modules made using LTCC technology have a hermetic and monolithic structure. This ceramic sheet of printed metal is then fired and sintered at a low temperature of about 850°C. This temperature range allows for the addition of low-resistivity conductor materials such as gold and silver paste. LTCC is a repeatable process and can be used to reliably produce large quantities of RF and microwave components measuring a fraction of the size of components fabricated with conventional substrate material. LTCC technology has the major advantage of multilayer integration of passive components along with active components at the top of the substrate by making cavities and sealing them with a seal ring to avoid coupling. This technology can be readily used in system-level packaging, i.e. system-in-package (SiP), in which passive and active components are merged into a single package, leading to miniaturization. Higher order or high rejection microstrip-based Band Pass Filter (BPF) requires a large area that inhibits the realization of RF SiPs. LTCC technology can be an alternative to the planar technology for the miniaturization of the BPF. The realized size of the LTCC filters is very small, and the placement of the components at different layers is very close to each other. This creates a chance of

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mutual coupling effect which may alter the performance of the circuit. The major challenge in the design of LTCC circuits involves the mitigation of coupling effects that arise due to closely placed components.

Brief Literature Review

A brief literature survey has been conducted to understand the realization and implementation of passive components using LTCC technology. Several studies have explored different filter topologies using LTCC technology.[1] LTCC filters are highly compact, and components are placed close to each other. This arrangement leads to mutual coupling, which affects circuit performance. The challenge is to model and verify parasitic effects through simulation. Stopband performance is crucial for isolation between transmission and receiving ports. A technique to improve stopband characteristics involves adding capacitors[1] at different layers and tuning their values to position Transmission Zeros (TZs) at desired frequencies. This method is widely used at lower frequencies. Another topology[2] uses a two-pole bandpass filter (BPF) with capacitive coupling between resonators. Cross-capacitive coupling generates transmission zeros at lower frequencies. A modified BPF structure[3] uses inductively coupled resonators. The TZs in this structure are controlled by shunt capacitors. Several filter structures simplify BPF design. A stepped impedance resonator (SIR)[4] determines the center frequency, while a coupling pad forms a transmission zero. This structure minimizes parasitic coupling. Out-of-band rejection improves by adding a capacitor within the coupled lines.[5] Transmission line lengths control TZ positions. A hybrid design[6] combining distributed and lumped elements further reduces BPF size. Here, interdigital capacitors and uncoupled transmission lines shape the filter's resonator section.

Various studies have explored high-rejection, miniaturized LTCC filters. However, improvements are still needed to reduce parasitic coupling and enhance rejection for applications like satellite communication. A common approach for TZ generation is capacitive coupling.[1,2] LTCC realizes capacitors as Metal-Insulator-Metal (MIM) structures, and transmission lines act as inductors. A limitation of this approach is that rejection depends on capacitance values, constrained by LTCC dielectric thickness (typically 5–10 mil). Increasing capacitance for better rejection requires larger metallic layers, increasing filter size. To overcome these limitations, some designs introduce extra coupling capacitors at the middle of the coupled lines.[3,5] Since capacitive tuning is restricted, distributed filter sections help model TZs.[4] However, lumped components limit these designs for high-frequency applications. Another technique[7] involves inductively coupled resonator tanks with a feedback capacitor between input and output. The feedback capacitor introduces TZ pairs—one in the lower and another in the upper stopband. With LTCC's multilayer capability, these lumped circuits can be realized using parallel plates for capacitors and metallic strips for inductors.

Negative coupling techniques are widely used in LTCC-based compact BPF designs. Some approaches[8] use coupled resonators with negative coupling coefficients. These designs feature asymmetrically tuned resonators with magnetic coupling. Negative coupling shifts the even-mode resonant frequency higher than the odd mode. A compensating inductor Lg[8] brings down the even-mode frequency without altering the odd-mode frequency. This compensation method enables narrowband BPF designs with small coupling coefficients. A novel technique uses open and short vias[9] to control the coupling coefficient and TZs. An open via is a post through the substrate without metal connection, while a short via connects to the metal surface. Open vias shift TZs upward, and short vias shift them downward, varying the coupling coefficient. Another study[10] explores wideband BPFs with independent TZs using coupled lines with open/short stubs. Source-load coupling[11] generates sharp rejection with two TZs near the passband.

Semi-lumped resonant units use parallel plate capacitors and via-hole inductors to form resonators. Adjusting the via height fine-tunes the operating frequency. Source-load coupling also helps control additional TZs near the passband. A dual-mode filter with T-shaped orthogonal feed lines[12] excites a coplanar square-loop resonator on the backside, forming a defected ground structure (DGS). This design produces an asymmetric response with two upper-band TZs. A similar dual-mode LTCC-based technique[13] suppresses harmonics by placing orthogonal T-shaped feed lines on one layer and a square resonator on another. Stepped impedance in the feed lines improves harmonic rejection.

As microwave frequency bands become congested, high selectivity and harmonic rejection are critical. Some studies use stepped impedance resonators and

DGS-based TZs for wideband rejection. However, extra circuits in LTCC layouts complicate integration and may introduce interference. A technique called discriminating coupling[14] selectively blocks unwanted signals while allowing required ones. This method is effective in second-order microwave and millimeter-wave BPFs, suppressing third and fifth harmonics. Another approach uses multilayer interdigital resonators[15] for quasi-elliptic filtering. A multilayer Dual Composite Right- and Left-Handed (D-CRLH) resonator[16] combines microstrip inductors and interdigital capacitors in LTCC. Transmission zeros depend on left- and right-hand resonator coupling. However, fabrication limits the coupling strength, restricting filter selectivity. Several studies[17,18] discuss LTCC-based RF frontends with multilayer BPFs and optimized transitions from coplanar waveguide to stripline. Further miniaturization and improved selectivity remain areas for research.

This study proposes a novel architecture to control coupling coefficients with adjustable TZs. A third-order grounded combline resonator is loaded with a capacitor. To reduce parasitic coupling, all ground vias are removed, and edge plating is used. Edge plating enhances RF grounding, reduces parasitic via inductance, and improves electrical connections. Selectivity is further improved by introducing a U-shaped structure below the grounded resonator. This structure couples non-adjacent resonators and forms an LC network to control TZs. An additional coupling pad between the resonators and U-shaped slot enhances resonator coupling and tunes filter bandwidth.

Other approaches[9,16] use open/short vias and D-CRLH resonators to control TZs. Open/short vias create additional parasitic inductances, making optimization difficult. Another method[16] enhances selectivity with compact D-CRLH resonators, but fabrication complexity restricts the filter order to second-order. A study[19] embeds stepped impedance stubs (SISs) in coupled lines (CLs) to control TZs using LTCC. However, folding distributed coupled lines into multilayer structures introduces unwanted MIM capacitors, forming additional parasitic LC networks. This issue makes SIS-based designs unsuitable for Ku-band and higher frequencies. Another technique uses capacitor-loaded stepped impedance resonators[20] to improve passband selectivity. Multiple TZs enhance selectivity, but the structure is complex and difficult to implement in multilayer LTCC. Miniaturization requires multiple folds of distributed elements, increasing unwanted parasitic coupling.

The proposed design is easier to fabricate, introduces higher filter orders, and improves selectivity with minimal capacitance and inductance values. The number of layers remains unchanged, and ground vias are minimized. A microstrip-to-stripline transition is used for RF signal feeding.

Modelling of the Proposed Structure of the Filter

The modelled structure of the proposed third order Band pass filter using LTCC technology is shown in Fig. 1. The proposed structure is constructed using five layers of dielectric with a complete metal layer at the bottom which acts as a ground. The basic topology that has been chosen for the proposed work is the grounded combline filter, the structure proposed is the simplest to avoid parasitic coupling between the elements buried within the layers. A loaded capacitor has been incorporated just above the resonator to make the circuit work for the desired center frequency. Using second metallic layer, a MIM capacitor has been constructed that represents a loaded capacitor for the resonator as shown in Fig. 1. Below the resonator a coupling pad is created for controlling the coupling between the resonators and fine tuning the bandwidth of the filter. A controlled or regulated transmission zero has been introduced to the upper side of the pass band as a result of U-shaped pattern on the fifth layer, this layer introduces coupling between non-adjacent resonators which controls the transmission zeros. Edge plating has been carried out for connecting the bottom ground layer to all the above layers, this technique of grounding helps to reduce parasitic effects due to formation of closely spaced vias for grounding. Proposed structure has three grounded resonators l_1, l_2 and l_3 loaded with three section MIM capacitor as l_{c1}, lc_2, lc_3. Length of

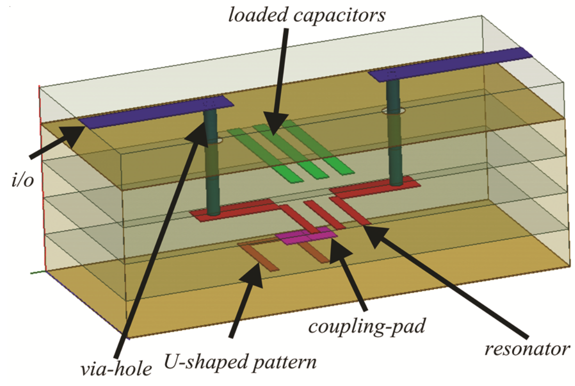

Fig. 1 — Proposed Structure of BPF

U-shaped pattern is determined by l_u. The design parameters are determined as follows (all in millimetres); l_1 = 1.65, l_2 = 2.6, l_3 = 1.65, l_{c1} = 1.98, l_{c2} = 1.98, l_{c3} = 1.98 and l_u = 2.82. The circuit size of the LTCC wafer is 6.5 mm × 2.58 mm × 0.89 mm.

Electrical equivalent of the proposed filter structure is shown in Fig. 2, electrical equivalent of the filter helps to analyse the effect of capacitances and inductances arises due to metal-ceramic structure. The equivalent circuit shows coupled transmission lines having length 'l'. The effective capacitance 'Cp' which is responsible for the coupling between the resonators is enhanced by introducing a coupling pad below the resonators. Apart from that the equivalent capacitance 'C_u' which represent the non-adjacent coupling, further enhancing the coupling, this capacitor 'C_u' along with the inductor 'L_u' (parallel C_u -L_u) represent U-shaped transmission line that is placed below the coupling pad. The capacitance 'C_d' is the equivalent MIM capacitor of the filter that represents the loaded capacitor for the resonator. Equivalent circuit values are depicted as C_u = 0.1pf, C_d = 2.0 pf and C_p = 0.5 nf, coupling between the resonators depends upon the spacing between then, lesser the spacing more the bandwidth, more the resonant modes are coupling, hence, capacitance C_p value will be more.

The structure proposed in this paper is simpler in design as compared to earlier reported architectures operating at higher frequencies. In this design all the equivalent circuit capacitors which control the selectivity of the filter can be controlled by changing the length and width of three metallic layers which makes the circuit simple and feasible for repeatability.

Analysis of the Resonating Modes of the Proposed Filter

Resonating mode analysis has been carried out to predict the behaviour of the proposed bandpass filter. In order to analyse the filter response, a small gap has been produced between the feedline and the resonator.

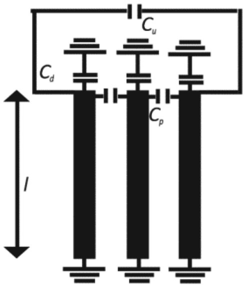

Fig. 2 — Equivalent Circuit of the Proposed BPF

As presented in Fig. 3 the resonating modes of the filter shows that there are three modes with one transmission zero on either side of the passband. The effect of variation of the length of U-shaped transmission line 'l_u' at layer 1 on the transmission zero is shown in Fig. 3(a). At l_u= 1.35 mm, the transmission zero appears at the lower side of the passband at 9.9 GHz. As l_u changes to 2.35 mm, transmission zero (TZ) appears near the higher side of the passband at 13.5 GHz. The change in the length of l_u shifts the TZs as shown in Fig. 3(a). This variation of l_u demonstrating the effect of the U-shaped pattern on the transmission zero and helps to understand the frequency response of the filter and its effect on insertion loss (S21) in dB.

Analysis of the coupling pad is shown in Fig. 3(b), where the change in the position of the coupling pad S_p from the open end to the grounded end of the resonator reflects the perturbation in the resonating modes. This leads to change in the coupling coefficient, resulting in the effect of insertion loss (S21) measured in dB with the change in frequency.

Resonating modes of a filter determines the quality of the filter and the basic structure of the filter that can be further optimized, it determines the energy stored by the resonating structure of the filter. More resonating modes in a particular operating frequency means more energy stored in that particular frequency which will give least insertion loss. Controlling Transmission Zeros (TZs) at a particular frequency can be analyzed by the behavior of the mode at that frequency, the energy should be minimum at that frequency. Selection of the particular mode which

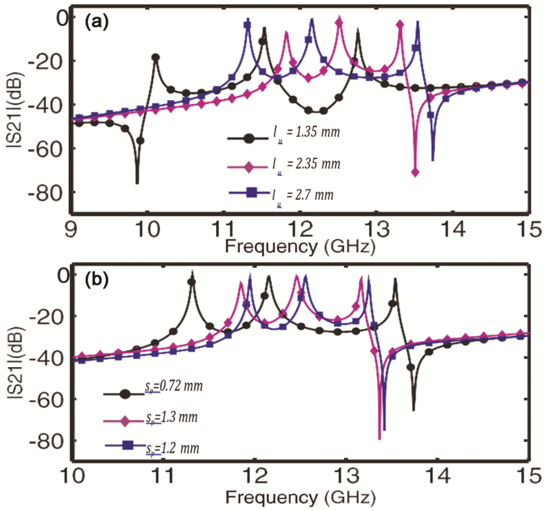

Fig. 3 — Analysis of Resonating mode (a) Effect of U-shaped pattern variation, (b) Effect of coupling pad

may be fundamental, 2nd harmonic or any higher mode depends upon the application of the filter and fabrication capability of the foundry as higher the modes the resonating structures will be very small.

Design and Simulation of the proposed filter

The prototype design reported in this paper is based on Chebyshev response. The return loss and the absolute bandwidth have been calculated depending upon the center frequency. Two major design parameters[1,10], i.e. coupling coefficients with external quality factors can be derived using the equation mentioned below w.r.t functional bandwidth (FBW).

$$Q_{ei}= (G_0\,G_1)\ (fBW)^{-1} \qquad \ldots (1)$$

$$Qeo= (G_nG_{n+1})\ (fBW)^{-1} \qquad \ldots (2)$$

$$M_{k,\ k+1}=(G_kG_{k+1})^{-1}(fBW), k=1\ to\ n-1 \qquad \ldots (3)$$

Q_{ei}, Q_{eo} = extrinsic quality considerations of input and output resonators respectively.

$M_{k,\ k+1}$ = coefficient of mutual coupling between the i^{th} and $(i+1)^{th}$ resonators.

The coupling coefficient and quality factor have been extracted by the utilization of the RF FEM solver, HFSS 17.2 version. In actual practice, the coupling-coefficient between the two resonators is associated with f_p and f_q respectively which are two primary resonant frequencies as mentioned.[10]

$$M_{k,\ k+1} = (f_p^{\,2} - f_q^{\,2})\ (f_p^{\,2} + f_q^{\,2})^{-1} \qquad \ldots (4)$$

Coupling gap as well as position and width of the coupling gap which is at layer 2 is determined approximately by Eq. 4. With the help of FEM solver, the external quality factor[10] can be calculated by:

$$Q_e = \omega_0/\Delta\omega_{\pm 90^\circ} \qquad \ldots (5)$$

where, ω_0 = resonating frequency

$\Delta\omega_{\pm 90^\circ}$ = absolute bandwidth between the spots that are 90° degrees apart with relation to its phase when it is at ω_0 on the phase plot of S_{11}.

Quality factor of bandpass filter is determined by the tapping position, variation in taping position helps in tuning the return loss of the filter using FEM solver in simulation. In the simulation set up, adaptive solution was carried out with maximum twenty number of passes with deltas of 0.02 (The algorithm refines the mesh until s-parameters converge below the certain value). Multilayer model of the proposed structure is created in HFSS, the boundary conditions for simulation set up is carried out as; finite conductivity for the ground plane as well as at side walls where edge plating is carried out and radiation boundary at the top to estimate any radiation effect of the multilayer structure.

Using this technique, a third order bandpass filter at Ku-band (12.75–13.0 GHz) has been designed. The proposed filter 3 dB bandwidth is 310 MHz Simulation is carried out using LTCC substrate of dielectric constant of 5.9. Each layer uses the thickness of 10 mil (1 mil = 0.01 inches).

The findings from the simulation indicate that the proposed filter has a frequency response of 12.7 GHz and an absolute bandwidth of 310 MHz. Achieved an image rejection of ~ 26 dB at 11.63 GHz at the lower side of the passband. (Payload Receiver is based on Low side injection). Also, there is a transmission zero located at 16.1 GHz to suppress further any unwanted harmonics. The simulated value of the insertion loss (S21) which is nearly 3dB with a return loss (S11) of 20 dB is shown in Fig. 4.

Each layout of the layers of LTCC filter is shown in Fig. 5. The 6th layer M_6 determines the input and output of the bandpass filter. M_5 is the fifth layer

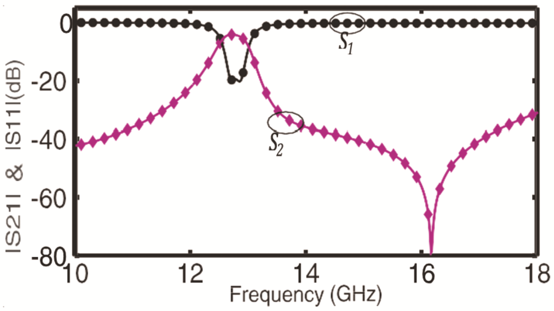

Fig. 4 — Simulated response of the proposed BPF

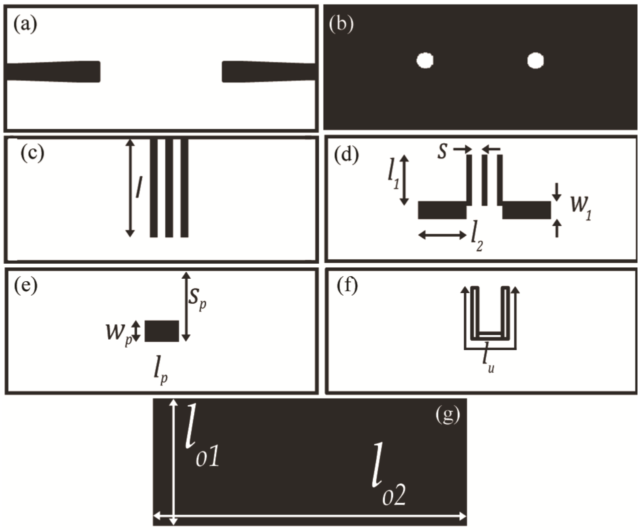

Fig. 5 — Layout description: (a) *M*6 (b) *M*5 (c) *M*4 (d) *M*3 (e) *M*2 (f) *M*1 (g) *M*0

Table 1 — Comparison of Present Design parameters with the reported Structures

Filter Order	Controlled Transmission Zero	Operating Freq. (GHz)	Dimension (mm)	Loss (dB)	Filter Structures
Three	NO	1.95	6.6×6.6×0.836	2.0	2,1
Two	NO	2.5	4.25×2×0.54	0.87	7
Three	NO	2.19	2×1.25×0.9	1.8	11
Three	NO	2.68	22.4×22.4×0.8	1.2	12
Three	NO	13.0	0.91×0.95 × 0.29	1.95	16
Three	YES	12.7–13.0	6.5×2.58×0.89	3.6	This work

which is actually ground for input/output feedline drawn at M_6, which constitute a microstrip structure. M_3(third layer) determines the resonator whose one end is grounded to the LTCC structure through edge plating and other end is open-ended. This resonator is connected to M_6 layer through via-hole, a cut has been created in the fifth grounded layer.M_4 (fourth layer) determines MIM capacitor which acts as a loaded capacitor for the grounded resonator. Edge plating technique has been used for grounding the resonators as well as loaded capacitors. M_2 (second layer) is used for the coupling pad layout, whereas U-shaped pattern is drawn at M_1 (first layer). M_0 represents the ground layer. Z-axis shrinkage factor has been taken into account during layout formation and simulation.

Comparison of our work with other designed bandpass filters published in literature is shown in Table 1. Design presented in this paper had an advantage of controlling the placement of transmission zero which can be controlled base on the requirement of high side or low side injection of Local Oscillator (LO) frequency. The present design is suitable for satellite receivers for noise rejection at image frequencies and can be implemented before mixer for sensitivity enhancement. The stack-up drawing (DXF) has been sent to the foundry for fabrication after DRC check with the foundry.

Conclusions

This analysis proposed an architecture that addresses multilayer parasitic coupling at higher frequencies that effects the filter performance and selectivity can be tuned by controlling the transmission zeros (TZs).

In this topology TZs can be placed within $f_c \pm 1.0$ GHz, further improvement can be achieved by designing a higher order filter. Present topology is the combline resonator which is wide band in nature (low Q), hence, getting further sharp rejection nearer to the center frequency requires further modifications in architecture. Source load coupling can be implemented in the structure for further enhancement of the selectivity.

The center frequency of the filter can be controlled by tuning the capacitance C_d of the loaded capacitors; moreover the tuning range of the filter depends upon the spacing between resonators which is a fabrication limitation, in LTCC technology. Modification in the structure for the improvement in the tuning range can be taken for future analysis.

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