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Miniaturized EBG Cavity Filter Loaded with Alumina 96 % for V-Band Applications

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The aim of the research, presented in this paper, is to investigate millimeter 3D rectangular metallic cavity filled with alumina 96 % dielectric substrate (Al_2O_3) suitable for microwave integrated circuit (MIC), with 9.4 relative permittivity value, and 0.006 dielectric tangent losses, for the design of small size filters. The total volume of the structure is $1.45 \times 1.45 \times 1$ mm^3. This cavity is considered as a band-pass filter operating in the range of 60 GHz frequency and intended for LTCC (system-in-package applications). In contrast, the filter presents an efficient EBG system with a rejection band at – 10 dB of 3.4 GHz within the frequency band centered at 57 GHz when the cavity is loaded with periodic metallic via (stems) that form coupled resonators. The choice of the dielectric substrate, metallic via, their dimensions and their type, enable to provide optimal characteristics, bandwidth of 4.3 GHz, transmission level of – 21 dB at centered frequency, low insertion losses of – 0.9 dB and Q factors. Obtained results are very promising for V-Band and mm-wave small-cell applications.

Keywords: Millimeter Filter, Alumina 96 %, Metallic via, EBG, V-Band.

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1. INTRODUCTION

Mobile telecommunication devices are ubiquitous, and their number continues to increase. By most estimates, 50 billion devices will be connected by 2020 [1]. As 5 G telecommunication systems are deployed to cope with the increasing demand, the need for compact and efficient millimeter filters is a reflection of the devices that are becoming increasingly widespread. However, most of the plans for long-term use involve the implementation at previously unutilized mm-wave frequencies. 28 GHz is roughly the most cited frequency, with slight shifts depending on the country [2, 3]. Some recent works have dealt with increased frequencies and enhanced insertion loss and rejection at these frequencies, such as M. Ali [4]. Other works done on microwave filters have been related to improving the Q factor, such as the integration of EBG structure in the cavity resonator, proposed by Michael et al. [5]. Other research works based on substrate integrated waveguide (SIW) for communication purpose as millimeter-wave, are presented by [6, 7]. The design of a millimeter cavity filter can be based on the choice of the substrate type or the geometrical shape of a circular or elliptical cavity, the filter design can have very high performance [8, 9]. A rectangular coaxial feed is used in the work presented by Wang et al. [10]. In order to obtain a micro machined cavity resonator, Amari et al. [11] have presented a theoretical pass-band filter designed by coupled resonators. The high-Q cavity filter was investigated by SOI-Based RF MEMS tuners [12] and work presented by Silicon Technology based Evanescent Mode [13].

In recent years, more sophisticated structures have been involved to design millimeter-wave filters; these are based on SIW and parallel coupled resonators, while others are based on 3D structures [14, 15]. Recent millimeter filters deal with miniaturized structures with multi-band or multi-mode. However, the manufacture of such filters remains more and more possible with new advanced technologies such as LTCC [16, 17].

In this paper, a rectangular small size cavity filled with alumina 96 % dielectric substrate (9.4 relative permittivity value and 0.006 dielectric tangents losses), loaded with silver via holes (with a conductivity of 6.1×10^7 S/m) to create EBG (electromagnetic band gap) system [18] is investigated. alumina 96 % (Al_2O_3) is one of the most popular ceramic substrates because of its excellent properties in terms of heat resistance, high mechanical strength, resistance abrasion, and low dielectric loss. Hence, alumina 96 % substrates are suitable for thick film applications. This ceramic is the workhorse of the microwave integrated circuit (MIC) business. The aim of our contribution is to design a millimeter band pass filter with high resonant frequency, low insertion losses and good quality factor Q using alumina 96 %. Filter optimization is obtained by a suitable choice of metallic via dimensions, quantity and arrangement. The insertion of additional capacitive effects when loading a metallic disk is also studied and compared.

2. THEORETICAL ASPECT

Theoretically for a rectangular cavity (Fig. 1) the resonance frequency is given by the relationship (1):

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$$f_r = \frac{c}{2\pi\sqrt{\varepsilon_r \mu_r}} \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{m\pi}{b}\right)^2 + \left(\frac{m\pi}{ac}\right)^2}, \quad (2.1)$$

where a, b and l represent the dimensions of the cavity; m, n and p represent the mode indices. The empty quality factor Q_0 is a measure of the cavity selectivity and is defined as:

$$Q_0 = \frac{f_r}{\Delta f}, \quad (2.2)$$

where f_r is the resonance frequency, Δf is the bandwidth at – 3 dB.

The results of these three methods approximately coincide. Therefore, around the resonance mode, a cavity can be represented by a resonant circuit *R, L, C*. In the case when the excitation is provided by coplanar lines, these couplings with sections of these lines can be indicated by perfect transformers.

The resonant frequency is given by [7]:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \quad (2.3)$$

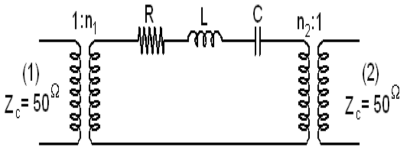

Fig. 1 – The coupled cavity equivalent circuit

2.1 Proposed Excitation and Metallic Disk

The choice of excitation fell on the "Lumped Port", because in practice the coupling of the resonator with its external environment is well done due to coplanar type excitation, etched into the metallization of the substrate upper face [19]. We therefore use localized excitation (Fig. 2). The spacing between the two excitation ports is estimated at 0.3 mm.

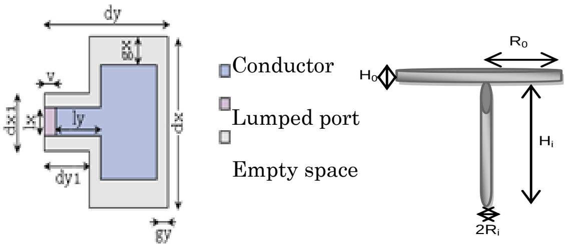

Fig. 2 – Excitation and disk geometrical dimensions

2.2 EBG Cavity Design and Capacitive Effects

We can realize a re-entrant cavity filled with alumina 96 % by adding a metallic via in the centre. In the case of TM_{110} mode, electric field is the most intense at the centre [20]. Fig. 3 shows the study structure.

Theoretically, for a given cavity, each improvement in the filter selectivity by changing excitation system is accompanied by increasing losses, and each decrease in losses leads to a drop in the quality factor of the filter. Table 1 lists all the proposed structure dimensions. The idea of periodic vias is chosen here so that it presents interesting properties, the periodicity is ensured in two dimensions, and the structure remains homogeneous in the third dimension. Additionally, the use of metal for the realization of periodic structures has several advantages.

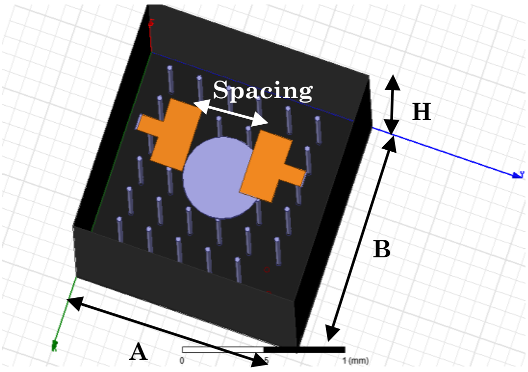

Fig. 3 – Cavity with 32 periodic metal holes and disk plot

Table 1 – Structure parameters and dimensions (mm)

Parameters	Values	Parameters	Values
A	1.45	V	0.02
B	1.45	dx	0.6
H	1	dy	0.3
H_0	0.008	H_i	0.47
R_0	0.25	R_i	0.015
l_x	0.1	l_y	0.13
g_x	0.03	dy_1	0.13
g_y	0.1	dx_1	0.25

In periodic metal structures, electromagnetic waves will be more strongly disturbed, and an EBG band will be created. The propagation of electromagnetic waves in such structures is governed by Maxwell's equations. The minimum centre-to-centre distance between the vias in our case is limited at 200 μm. Insertion of a metallic disk into the cavity center that does not entirely cross the substrate will create an additional capacitive effect in the structure [18]. If the electrical series *RLC* model is used in localized elements of the resonator, this capacitive effect is added to the capacitance and inductance representing the resonance (Fig. 4).

$$f_r = \frac{1}{2\pi\sqrt{L_R(C_R + C_D)}}. \quad (2.4)$$

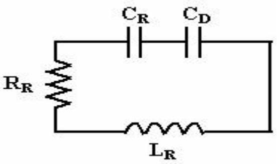

Fig. 4 – Modeling of the capacitive effect on *RLC* circuit

3. RESULTS AND DISCUSSION

In practice, the load quality factor Q_L defined at the resonant frequency is a dimensionless index for quantifying the resonator selectivity. It must be calculated from the electrical response in S_{21} transmission as follows:

$$Q_L = \frac{f_r}{f_2 - f_1} \qquad (3.1)$$

where the frequencies f_1 and f_2 correspond to the bandwidth taken at – 3 dB and f_c is the resonant frequency, for which the level of losses is minimal.

The empty quality factor Q_0 is also a dimensionless index that specified the resonator intrinsic electrical performance. Typically, an increase in Q_0 decreases the insertion losses and optimizes the rejection level. In this case, Q_0 can be calculated using the expression:

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{ext}}, \qquad (3.2)$$

Q_{ext} is the external quality factor, it models the excitation system losses:

$$Q_{ext} = \frac{Q_L}{|S_{21}(f_r)|} \qquad (3.3)$$

and

$$Q_0 = \frac{Q_L}{1 - |S_{21}(f_r)|}. \qquad (3.4)$$

To determine the parameters of the cavity filter, it is sufficient to draw the S parameters as a function of frequency. Without vias and capacitive plot, it can be observed from Fig. 5 that the cavity loaded with alumina 96 % is only a band pass filter at – 3 dB of 2.7 GHz, centered on the resonance frequency of 56.66 GHz of the first TM_{110} mode. EM simulation of our resonator taking into account the assumed substrate properties and silver conductivity leads to an empty Q_0 factor value of 116.

Thus, Table 2 summarizes characteristics of empty resonator filter. A rejected bandwidth at – 10 dB close to 3.5 GHz is also observed in the considered band pass range, which confirms the creation of an optimized EBG system than the one given in [18]. By creating defects in the device system, we can also observe interesting tuning effects of pass band filter with default 3.

Fig. 6 shows the transmission and reflection coefficients of the cavity loaded by alumina 96 % dielectric substrate and 32 periodic metallic vias for different cases, by creating defects in the periodic structure (by elimination of 4, 8 and 12 vias). The insertion of a metallic via generates the creation of a pass band system centered at 57 GHz with a band pass at – 3 dB close to 7.5 % and transmission level of about – 21 dB.

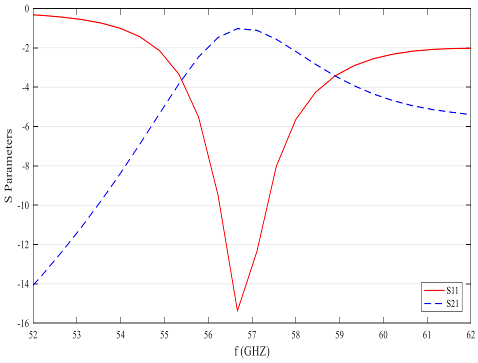

Fig. 5 – S parameters of empty resonant cavity

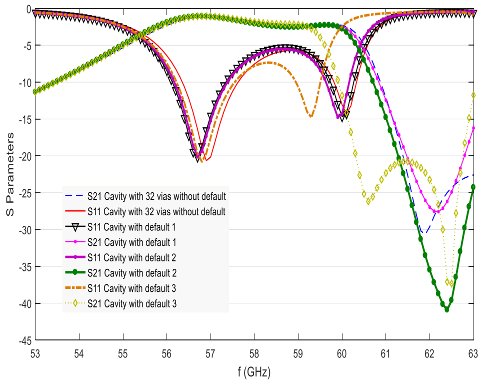

Fig. 6 – S parameters of alumina 96 % filters loaded with 32 periodic metallic holes

Table 2 – Summary of filter characteristics loaded with alumina 96 %

Resonator center frequency	f_r	56.66
Bandwidth (– 3 dB)	Δf	5 %
Insertion losses (dB)	$1 - \lvert S_{21}(f_r) \rvert$	– 0.9
External quality factor	Q_{ext}	25.6
Unloaded quality factor	Q_0	116

Table 3 – Comparison between alumina 96 % and silicon

Material	Silicon[18]	Alumina
ε_r	5.9	9.1
Tangent losses	$1.3\ 10^{-3}$	0.006
f_c (GHz)	42.6	56.6
Δf (GHz)	3.6	4.3
Insertion losses (dB)	– 0.6	– 0.9
Q_{ext}	23	32
Q_L	20	26
Rejection band at – 10 dB (GHz)	0	3.4

For the same dimensions of a cavity, Table 3 summarizes the comparison of filter function characteristics simulation results using alumina 96 % or silicon [18]. One can see from Table 3 that silicon offers better filter selectivity with minimal losses, but band pass, external and loaded Q factors provided by alumina 96 % filter are optimal. Furthermore, the rejection band of 3.4 GHz at – 10 dB was observed from our results, which is not the case for results of [18].

The capacitive effect introduced into the functioning of the cavity modifies its resonant frequencies. We can observe from Fig. 7 the creation of a multi pass band system, the first resonance frequency is decreased to 5 GHz with a bandwidth of 3 % at – 3 dB, the second one remains centered at 57 GHz with a bandwidth of 8 % at – 3 dB. The capacitive reinforcement is therefore accompanied by an improvement of the Q factor due to an increase in the loaded quality factor Q_L, since in this area the electromagnetic field is extremely concentrated. Note that the capacitive effects introduced into the functioning of the resonator will be a function of the distance between the upper limit of the via and the upper face of the metallized cavity, as well as of the surface of disk [18].

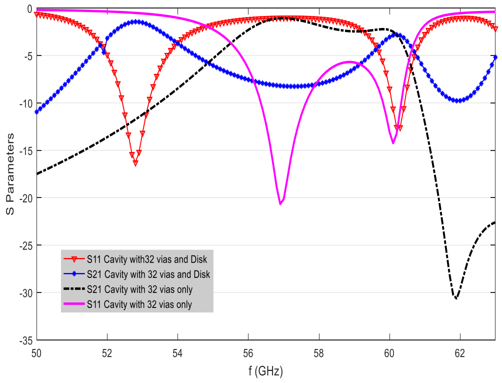

Fig. 7 – *S* parameters of alumina 96 % filters loaded with 32 periodic metallic holes and metallic disk

4. CONCLUSIONS

In this paper, a rectangular cavity based on 32 metallic via holes and a capacitive metallic disk loading with alumina 96 % have been simulated and investigated. The filter provides an optimal passband of 4.3 GHz at – 3 dB and an interesting EBG rejected band at – 10 dB close to 3.4 GHz. The use of alumina 96 % has approved interesting filtering characteristics comparing to other substrates usually used in the fabrication of microwaves filters, known as the stability, minimum losses, low cost and facility of integration in millimeter cavity filters with improved *Q* factors. The most direct application of this contribution is the use of multi pass band frequencies for V-band applications, with a rejection band gap used as a stop band filter.

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Мініатюрний порожнинний фільтр EBG, заповнений глиноземом 96 % для додатків V-діапазону

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Метою представленої роботи є дослідження міліметрової 3D прямокутної металевої порожнини, заповненої діелектричною підкладкою з глинозему 96 % (Al_2O_3), придатної для мікрохвильової інтегральної схеми (MIC), із значенням відносної діелектричної проникності 9,4 і тангенсом кута діелектричних втрат 0,006 для проектування малогабаритних фільтрів. Загальний об'єм конструкції становить 1,45×1,45×1 мм^3. Ця порожнина розглядається як смуговий фільтр, що працює в діапазоні частот 60 ГГц і призначений для додатків LTCC (system-in-package applications). На відміну від цього, фільтр представляє ефективну систему EBG з режекторною смугою на рівні – 10 дБ частоти 3,4 ГГц в діапазоні частот з центром на 57 ГГц, коли в порожнину завантажуються періодичні металеві наскрізні отвори, які утворюють зв'язані резонатори. Вибір діелектричної підкладки, металевих наскрізних отворів, їх розміри та тип дозволяють забезпечити оптимальні характеристики, пропускну здатність 4,3 ГГц, рівень передачі – 21 дБ на центральній частоті, низькі внесені втрати – 0,9 дБ та добротність *Q*. Отримані результати є дуже багатообіцяючими для застосування у малих елементах V-діапазону та мм-хвиль.

Ключові слова: Міліметровий фільтр, Глинозем 96 %, Металевий наскрізний отвір, EBG, V-діапазон.