Design of an integrated THz electromagnetic crystals (EMXT) cavity filter

Kai Zhou *, Yong Liu and Chao Zheng
School of Information and Electronics, Beijing Institute of Technology
South Zhongguancun Street, Haidian District, Beijing 100081, P. R. China
* Email: zkbit1227@163.com

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Abstract: An electromagnetic crystals (EMXT) cavity filter with photonic band gap (PBG) structure is analyzed and a narrowband filter operating at around 0.5 *THz* is designed. The filter is simulated using the finite element method and it can be fabricated by micro-electromechanical systems (MEMS) technology, due to its low cost, high performance and high processing precision. The simulation results show the filter has a good performance. The passband bandwidth is 7%, the rejection at one time bandwidth out of the passband is larger than 30 *dB*, and the insertion loss in the passband is less than 1 *dB*.

Keywords: Terahertz, Cavity filter, PBG Structure

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1. Introduction

The filter is a key device in communication, radar and imaging systems. Photonic band gap (PBG) structures, or photonic crystals may be a good choice to use for the design of THz passive components [1-3]. The PBG components have low loss and excellent capability of heat dissipation. PBG components possess great research and application values in the THz field, especially for the THz functional components [4-6]. The 2-D PBG waveguide has similar electromagnetic field distribution and similar transmission characteristics compared to traditional rectangular metal waveguide at the lower part of THz band [7]. Consequently, microwave approach is applied to investigate the integrated PBG components, termed electromagnetic bandgap structures (or EMXT), which are composed of periodic metallic and/or dielectric cells [8, 9].

The size of passive components is closely related to wavelength at THz band. Thus, micro-electromechanical systems (MEMS) technology, due to its low cost, high performance, and high processing precision, is very suitable for THz passive components devices fabrication [10].

In this paper a photonic band gap (PBG) metal cavity filter operating at around 0.5 *THz* is designed, which is manufactured by the MEMS technique DRIE (deep reactive ion etching). The simulation results show that the passband bandwidth is 7%, the rejection at one time bandwidth out of the passband is larger than 20 *dB*, and the insertion loss in the passband is less than 1 *dB*.

2. Filter design

The EMXT cavity filter is based on the dual-mode filter theory and the design principle is given by the EM analysis method [11]. Usually a resonator unit of the dual-mode filter includes rectangular cavity, circular cavity and elliptical cavity(not discussed in this paper).

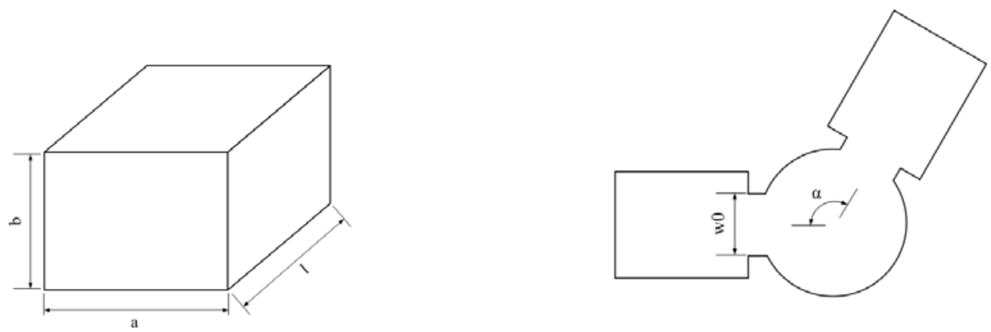


Fig. 1 (a) rectangular cavity (b) circular cavity

As shown in Fig. 1(a), each rectangular cavity provides transmission pole(s), and the higher order mode interactions are used to implement transmission zero(s) to increase the filter selectivity. To find the modal combinations which are possible in a rectangular resonator of sides a, b and l, we first impose that the eigenvalue relative to the dimension b is equal to zero.Second, we impose the condition that both modes resonate at the same frequency,namely

$$(\frac{m\pi}{a})^2 + (\frac{n\pi}{l})^2 = (\frac{p\pi}{a})^2 + (\frac{q\pi}{l})^2 \tag{1}$$

The subscripts m,n refer to the first mode TE_{m0n} and p,q refer to the second mode TE_{p0q}. Further expression is given as

$$\frac{a}{l} = \sqrt{\frac{m^2 - p^2}{q^2 - n^2}} \tag{2}$$

Then after choosing TE_{m0n} and TE_{p0q} two orthogonal modes, the resonant frequency can be estimated by

$$f_0 = \frac{c_0}{2\sqrt{\varepsilon_r}}\sqrt{(\frac{m}{a})^2 + (\frac{n}{l})^2} \tag{3}$$

Thus,the center frequency of the filter is determined. Finally The modal indexes m and p (and n and q) must be different in order to obtain a dual-mode operation.On each side of the resonator, the field distributions of the resonant modes should be orthogonal,thereby allowing for the dual-mode operation. The opposite directions of the magnitude between the two orthogonal modes in the cavity vanish the transmission path and create the transmission zero. The transmission zero position is determined by modifying the dimensions of the cavity to control the quantity of the negative coupling between the two modes. The closer the transmission zeros to the cutoff frequency,the sharper the passband to stopband rolloff slope [11].

Circular cavity resonator is given in Fig. 1(b). The working mode of dual-mode filters with circular cavities is TM_{110} while that of dual-mode filters with rectangular cavities is TE_{102} and TE_{201}. Every dual-mode filter cavity presents two transmission zeros (TZ) and two poles. The first zero, which is approximately equal to the eigenfrequency of the cavity TM_{110} mode, is close to the passband and it can increase attenuation slope in the upper passband.It is similar to the zero of the aforementioned filter with rectangular cavities, but it exhibits different characteristic. The second zero is decided by angle α.It is in the stopband and close to the TM_{210} mode. The proper value of α is between 100 and 130 degrees. Two poles below the first zero is used to control the passband bandwidth[12]. The expression of the resonant frequency is given by

$$f_{\mathrm{r}} = \frac{K\upsilon}{2\pi} = \frac{c}{2\pi\sqrt{\varepsilon_r}}\sqrt{(\frac{v_{mn}}{R})^2 + (\frac{p\pi}{l})^2} \tag{4}$$

m, n and p refer to the mode TM_{mnp} . v_{mn} is the n-th root value of m-order Bessel function. The wave at a frequency out of the passband is almost totally reflected from the cavity. So the wave must be a standing wave. The node of standing wave is just appearing at the output port at a specific frequency, forming the transmission zero. The passband characteristics are affected by different angle α [9].

Generally, the unloaded quality factor of the rectangular cavity is slightly lower than that of the circular cavity. The unloaded quality factor of substrate integrated waveguide(SIW) square, circular, and elliptic cavities by numerical simulation is listed in Ref.[9]. Considering the insert loss and passband to stopband rolloff slope, the filter given below is based on three cascaded circular cavities with α=120° .

At THz band, insertion loss of the EMXT cavity filter includes reflection loss, conductor loss and leakage loss. The leakage loss is caused due to the energy leakage through small apertures between metal posts. The thickness and roughness of gold layer should be considered in the passive components fabrication with MEMS process. The thickness must be larger than skin depth and the roughness affects insert loss directly.

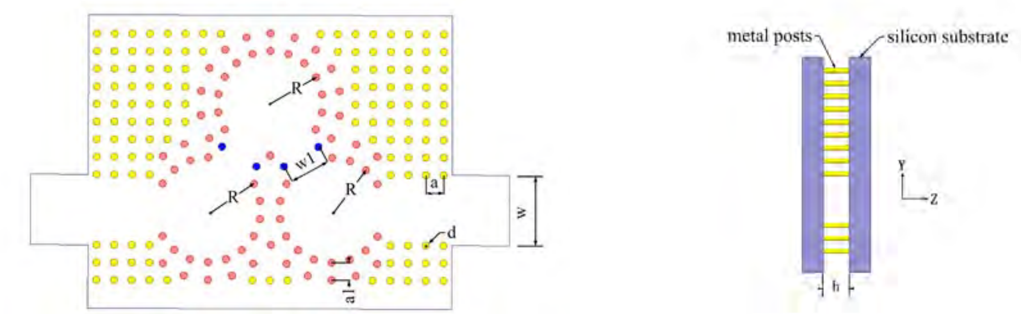
The exact parameters cannot be obtained easily with an analytical solution. The EMXT cavity filter is simulated and further optimized by using the commercial software HFSS which is a 3-D full wave electromagnetic field simulation software based on Finite Element Method (FEM).

3. Design of the EMXT cavity filter at 0.5THz

A 0.5 *THz* EMXT cavity filter is designed based on the aforementioned microwave approach. The filter structure is shown in Fig. 2. The structure consists of two PBG waveguide and three circular cavities, which are the defects in the lattice in the form of removed posts. Regular WR1.9 (483 $\mu m \times 241$ μm) metal waveguides can be connected to the PBG waveguides, and the power will transmit from one waveguide to another by the excited TE_{10} mode.

The cavities can be formed by either removing several posts from the structure or by altering the size of a post altogether. The frequency was tuned to the correct value by adjusting the geometry of the filter.

The lattice constant is a=120 μm, radial distance is a1=120 μm and the diameter of the post is d=48 μm. Width of the PBG waveguide is w=483 μm and height of the structure is h=241 μm.



(a) (b)

Fig. 2 Configuration of the EMXT cavity filter with the geometry parameters R and w1. R is the radius of the cavity and w1 is the width of coupling aperture.(a) Structure of the 0.5 *THz* narrowband filter (b) The section of the 2-D PBG waveguide

Primary model is simulated and optimized by HFSS software and the filter components parameters are shown in Table. 1.

Tab. 1 Design parameters of the 0.5 *THz* narrowband filter

Material of the posts	Silicon posts coated with gold layer
Diameter of the post (d)	48 μm
Lattice constant (a)	120 μm
The radius of the cavity (R)	357 μm
Width of coupling aperture (w1)	120 μm
Radial distance (a1)	120 μm
Width of the PBG waveguide (w)	483 μm
Height of the structure (h)	241 μm

4. **Results and discussion**

The simulated S_{21} are presented in Fig. 3 and Fig. 4 with different lattice constant and different radius of the cavity, respectively. It can be seen that: (i) Center frequency of the passband increases while lattice constant a increases from 80 μm to 120 μm with d=0.2a . (ii) Passband range is very sensitive to the radius of cavity R.

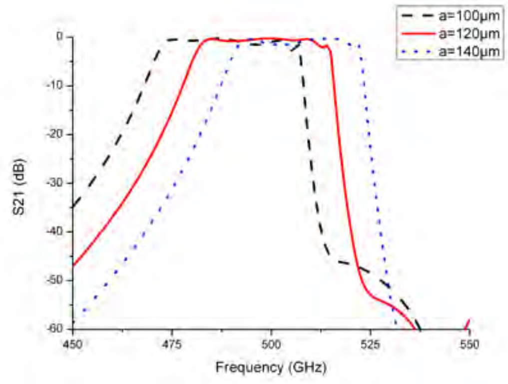


Fig. 3 Simulated S_{21} of the EMXT filters with a=100 μm, 120 μm, 140 μm and d=0.2a .

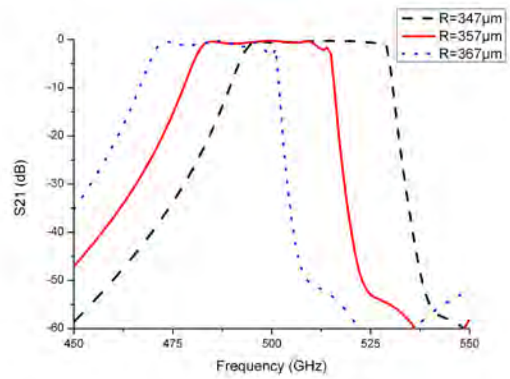


Fig. 4 Simulated S_{21} of the EMXT filters with R=347 μm, 357 μm, 367 μm.

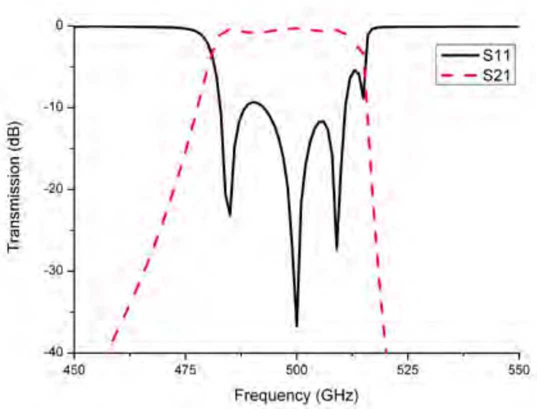


Fig. 5 Simulated transmission through the 0.5 *THz* narrowband filter.

Other parameters have also been optimized to get a good performance. Simulated transmission characteristics of the filter are plotted in Fig. 5. The passband range is from 0.482 *THz* to 0.516 *THz*. The fractional bandwidth is 7%, the rejection at one time bandwidth out of the passband is larger than 30 *dB*, and the insertion loss in the passband is less than 1 *dB*.

Simulated transmission characteristics of the filter considering the thickness and roughness of gold layer required by the MEMS process are plotted in Fig. 6.

The thickness is set to 200 *nm* and the roughness is set to 700 *nm*, 2 *nm* and 150 *nm* in the structure. Insertion loss at 0.5 *THz* increases from 0.3 *dB* to 1 *dB*. This is because metal in the

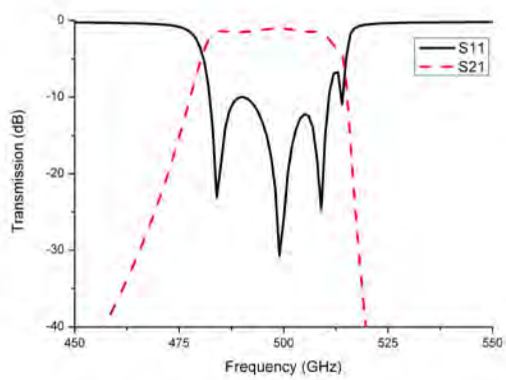


Fig. 6 Simulated transmission through the 0.5 *THz* narrowband filter considering the thickness and roughness of gold layer.

simulated model of Fig. 5 is set to perfect conductor. The insertion loss is caused by reflection and leakage loss through small apertures between metal post. But insertion loss in Fig. 6 also includes the ohmic losses of the conductor itself.

Notice that the upper sideband and the lower sideband are not symmetric in Fig. 5. The passband to stopband rolloff slope of the filter is very sharp. There are multiple resonant points in the passband. The phenomenon can be improved through further optimization of the EMXT cavity structure.

5. Conclusion

An EMXT cavity filter with photonic band gap (PBG) structure is investigated. MEMS due to its low cost, high performance, high processing precision is very suitable for THz passive components devices fabrication. Based on the theory of dual-mode filter, an EMXT cavity filter with PBG structure is designed with microwave approach. And a narrowband filter operating at around 0.5 *THz* is designed. Simulation results show that the designed filter has a good performance of filtering. Meanwhile, the 0.5 *THz* filter has a large feasibility to realize through the simulation analysis of the thickness and of roughness of gold layer required by the MEMS process. The filter can be employed in THz radar, communication and imaging systems.

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