Short Papers

A Dual-Plane Comb-Line Filter Having Plural Attenuation Poles

Toshiaki Kitamura, Yasushi Horii, Masahiro Geshiro, and Shinnosuke Sawa

***Abstract*—In this paper, a dual-plane comb-line filter having plural attenuation poles is proposed. We investigate the filtering characteristics from both experiments and numerical simulations by means of the finite-difference time-domain method. It is shown that this filter has attenuation poles just above, as well as below the passband and that intersections between the curves of input susceptance of the even and odd modes agree with the attenuation-pole frequencies. Furthermore, it is demonstrated that, by changing the position of the metal pin, which connects two resonators, we can change the input susceptance of the odd mode alone and, hence, regulate the attenuation-pole frequencies.**

***Index Terms*—Attenuation pole, comb-line filter, dual plane, FD-TD method.**

I. Introduction

Cellular phones are usually equipped with comb-line filters, which have an advantage that the frequency characteristics around the passband can be greatly improved by attenuation poles. Besides comb-line filters, many other types of filters that have attenuation poles around the passband have been proposed thus far. Attenuation poles play a significant role, not only to compress the transmission level of the stopband, but also to sharpen the passband response [1]–[7]. The mechanism to create attenuation poles has also been studied theoretically by several workers [8]. Utilizing the conductor-backed coplanar waveguide (CPW), we have already proposed a dual-plane comb-line filter, which has an attenuation pole just below the passband [9], [10]. By arranging two resonators face to face beyond the substrate, stronger coupling between them can be achieved and, thus, a wider passband can be realized in comparison with conventional filters, which arrange two resonators in parallel on one plane [1]–[4]. However, the filtering characteristics of the device are not sharp enough above its passband. In this paper, we propose a dual-plane comb-line filter that has attenuation poles both below and above the passband to sweep out this shortcoming. We investigate the filtering characteristics from both experiments and numerical simulations by means of the finite-difference time-domain (FD-TD) method. The frequency characteristics of scattering parameters show that this filter has a very sharp response above, as well as below its passband. For the filter proposed in this paper, the behavior of attenuation poles also differs from that of the conventional comb-line filters; hence, we investigate it by using the input susceptance calculated by FD-TD simulation. Furthermore, it is demonstrated that, by changing the position of the metal pin, which connects two resonators, we can change the input susceptance of the odd mode alone and, hence, regulate the attenuation-pole frequencies.

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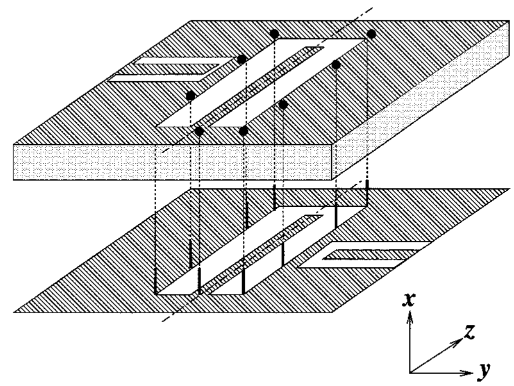

Fig. 1. Basic structure of a dual-plane comb-line filter based on the conductor-backed CPW.

II. Basic Principles

Fig. 1 illustrates a basic structure of the dual-plane comb-line filter based on the conductor-backed CPW. Simple quarter-wavelength resonators of the same structure are arranged on both sides of the substrate. Several metal pins penetrate the substrate around the resonators to connect metallized planes on both sides [4]. For I/O ports, a finite length of CPW is connected to each resonator through an appropriate length of tapping wire. The metallization patterns on the upside and underside are symmetric to each other with respect to the center axis of the resonators (the dashed–dotted lines in Fig. 1).

Fig. 2 schematically shows a common structure of the comb-line filter. Here, Y_e and Y_o represent the characteristic admittances of the even and odd modes, respectively, and l is the length of the resonator. The C's represent additional capacitance, which appears on the open end of the resonator. In Fig. 2, the input susceptance of the even and odd modes can be written as follows [8]:

$$B_{\text{in}}^{e} = -Y_e \cot \beta_e l + \omega C \tag{1}$$

$$B_{\text{in}}^{o} = -Y_o \cot \beta_o l + \omega C. \tag{2}$$

The equivalent circuit of this filter can be illustrated as in Fig. 3 in terms of the input susceptances of the even and odd modes B_{in}^{e} and B_{in}^{o}, and the attenuation-pole frequency is determined by the following equation:

$$B_{\text{in}}^{o} = B_{\text{in}}^{e}. \tag{3}$$

Flow lines of electric field of the even and odd modes of the dual-plane comb-line filter shown in Fig. 1 can be illustrated as shown in Fig. 4. The odd mode has dense flow lines of electric field between the center conductors. As a result, the effective dielectric constant of the odd mode is considered to be larger than that of the even mode.

The input susceptance of the even and odd modes of the filter in Fig. 1 can be drawn schematically, as shown in Fig. 5. In this figure, ω_e and ω_o, where the input susceptance of each mode vanishes, represent the resonant frequencies. Since this filter is a dual-plane type, the difference of effective dielectric constant between the even and odd modes is more determinative to the resonant frequency than the frequency dependence of Y_e and Y_o. Therefore, the resonant frequency

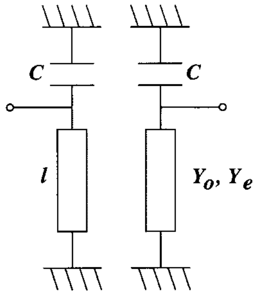

Fig. 2. Schema of the comb-line filter.

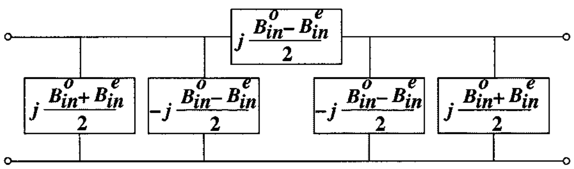

Fig. 3. Equivalent circuit of the comb-line filter.

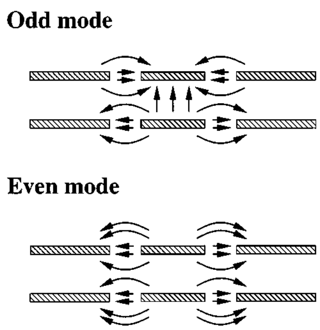

Fig. 4. Electric field lines of the even and odd modes standing on the comb-line filter.

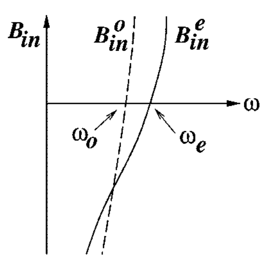

Fig. 5. Schematic drawing of the input susceptance of the even and odd modes.

of the odd mode becomes lower than that of the even mode. Furthermore, since the derivative of the input susceptance of the odd mode with respect to ω is larger than that of the even mode, the curves of the input susceptance of both modes intersect below the passband. Consequently, in contrast with conventional uniplane comb-line filters based on the CPW, which have an attenuation pole above their passband, the present filter has an attenuation pole below its passband. In Section III, we actually calculate the input susceptance of the even and odd modes by means of the FD-TD method.

It would be possible to improve the filtering characteristics above the passband of this filter if the curves of input susceptance of both modes had additional intersections, which means the emergence of other attenuation poles, above the passband by changing the structure of the resonators. In this study, we have found such structural parameters by numerical examination of filters that are equipped with step impedance resonators (SIRs) [11].

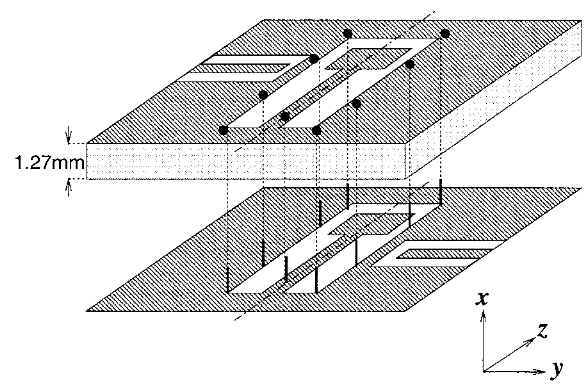

Fig. 6. Proposed dual-plane comb-line filter with SIRs.

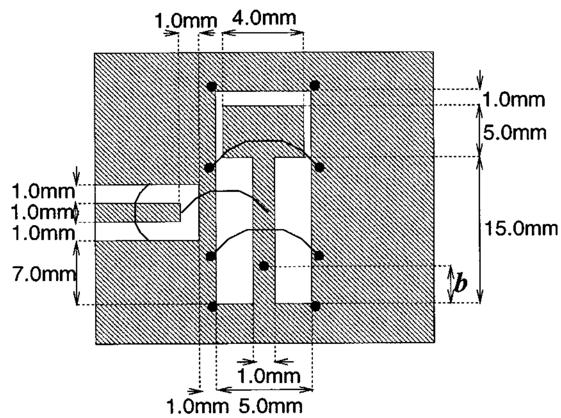

Fig. 7. Metallization pattern of the dual-plane comb-line filter with SIRs.

III. Numerical Analysis and Experiment

Fig. 6 illustrates the filter that we propose in this paper and the coordinate axes for the numerical analysis. The SIRs are fabricated on each side of the substrate whose relative permittivity and thickness are 10.2 and 1.27 mm, respectively. Due to the structural symmetry of this filter, the structural parameters on the underside are all the same as on the upside.

The metallization pattern on one side of the substrate is shown in Fig. 7. The SIR is constructed with a narrower line (1.0-mm wide and 15.0-mm long) and a wider one (4.0-mm wide and 5.0-mm long); hence, its total length sums to 20.0 mm. Experiments and numerical calculations are carried out with b, the position of the metal pin, which connects two resonators, as an adjustable parameter.

For experiments, an SIR-equipped dual-plane comb-line filter is manufactured on an RT/Duroid 6010LM substrate of 1.27-mm thickness and 10.2 relative permittivity by using a computer-aided design (CAD)-installed automatic cutting machine. Copper wires of 0.1-mm diameter and 7.0-mm length are soldered onto this metallization pattern as the tapping wires, which connect the resonators and I/O ports.

On the other hand, the same filter is modeled on Yee's mesh consisting of 20 $\times$ 80 $\times$ 110 cells in the numerical analysis by means of the FD-TD method; each cell size is assumed to be 0.635 mm in the x-direction and 0.5 mm in both y- and z-directions.

Fig. 8 shows the frequency characteristics of the transmission parameter $|S_{21}|$ and the reflection parameter—$|S_{11}|$ when $= b0.0$ mm. It is easily understood from the figure that two other attenuation poles are created just above the passband in addition to that below the passband. This feature makes the filtering characteristics preferably sharp

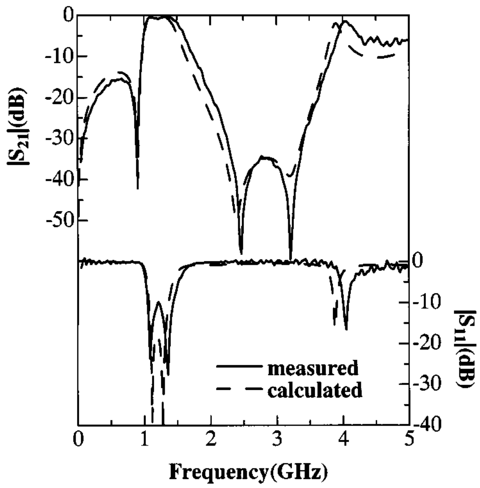

Fig. 8. Frequency characteristics of the scattering parameters when the metal pin is set at $b = 0.0$ mm.

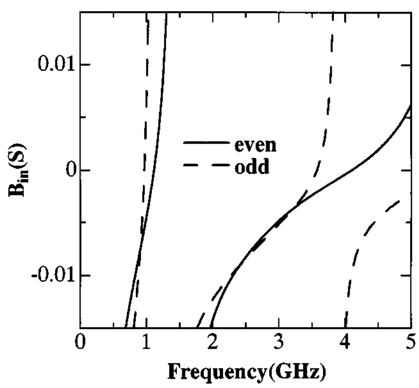

Fig. 9. Theoretical characteristics of the input susceptance of the even and odd modes when the metal pin is set at $b = 0.0$ mm.

on both sides of the passband. This figure also indicates that the experimental results shown by the solid line are in good agreement with the theoretical findings indicated by the dotted line.

Next, we show in Fig. 9 the frequency characteristics of the input susceptance $B_{\rm in}(S)$ for both even and odd modes.

For the filter illustrated in Fig. 6, the input susceptance of the even mode is calculated from

$$B_{\rm in} = {\rm imag}\left[\frac{1 - S_{11}(f)}{1 + S_{11}(f)} \cdot Y_0(f)\right] \tag{4}$$

by substituting $S_{11}(f)$ at the observation point on the input port. For the even mode, we excite electric fields having the same sign on the excitation planes, which are placed in the input and output ports at the same distance from the dashed–dotted lines in Fig. 6 so that we have the equivalent voltage on both resonators on the upside and underside. In (4), ${\rm imag}[]$ means taking an imaginary part of the quantity in the brackets and $Y_0(f)$ is the characteristic admittance of the conductor-backed CPW used for the I/O ports. In this study, we choose 50-Ω lines for them. The input susceptance of the odd mode is calculated in quite a similar manner. The only difference is that electric fields having the opposite signs are excited on both resonators. In Fig. 9, the curves of the input susceptance intersect at three different frequencies: $f = 0.91$ GHz, 2.40 GHz, and 3.21 GHz, and these frequencies agree with those of the attenuation poles in Fig. 8. When simple quarter-wavelength resonators without SIRs are adopted, the curves of the input susceptance have only one intersection below the passband, as mentioned in Section II. We obtain two more intersections above the passband by adopting SIRs and tuning their structural parameters.

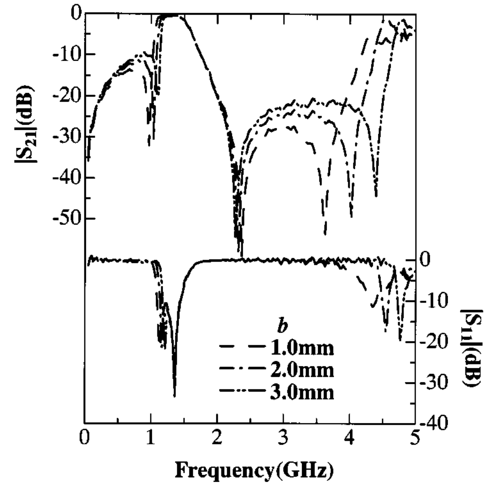

Fig. 10. Experimental characteristics of the scattering parameters with b as a parameter.

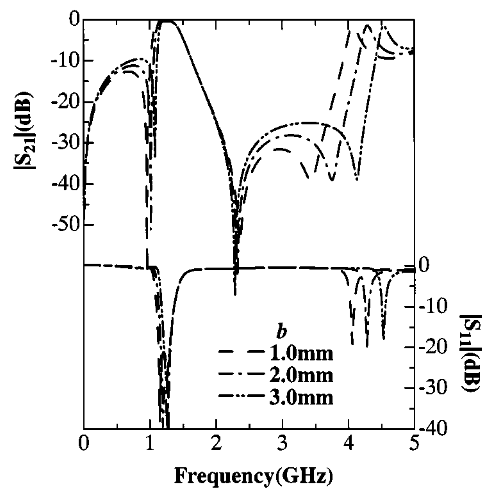

Fig. 11. Theoretical characteristics of the scattering parameters with b as a parameter.

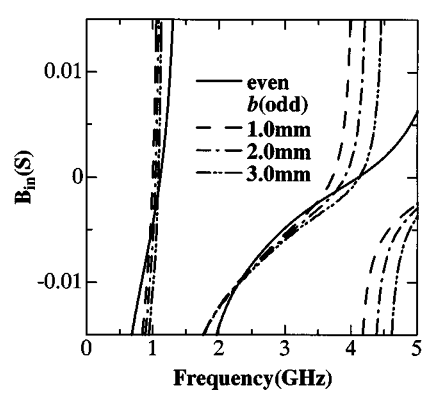

Fig. 12. Theoretical characteristics of the input susceptance of the even and odd modes with b as a parameter.

Figs. 10 and 11 show the frequency characteristics of $|S_{21}|$ and $|S_{11}|$ with b as a parameter: experimental data in Fig. 10 and numerical results in Fig. 11. Furthermore, the frequency characteristics of the input susceptance of the even and odd modes are shown in Fig. 12.

From Figs. 10–12, we come to the following conclusions. For the odd mode, when b becomes larger, the equivalent length of the resonator becomes shorter and, hence, the curve of its input susceptance shifts to the higher frequency region. On the other hand, since two resonators are always in the same electric potential for the even mode, varying b never changes its input susceptance. Therefore, when b becomes larger, the intersections between the curves of the input susceptance of both modes, i.e., the attenuation pole frequencies, move toward the higher frequency region. In this case, the attenuation pole around 4 GHz is most sensitive because the input susceptance of the odd mode shows the largest change for varying b.

Consequently, it is reasonable to tell that the attenuation-pole frequencies can be regulated by changing the position of the metal pin, which connects two resonators.

IV. Conclusions

In this paper, we have proposed a dual-plane comb-line filter having plural attenuation poles. The filtering characteristics have been investigated from both experiments and numerical simulations by means of the FD-TD method. It has been shown that this filter has attenuation poles just above, as well as below the passband, and that this feature makes the filter response preferably sharp. It has also been shown that intersections between the curves of the input susceptance of the even and odd modes agree with the attenuation-pole frequencies. Furthermore, it has been demonstrated that, by changing the position of the metal pin, which connects two resonators, we can change the input susceptance of the odd mode alone and, hence, regulate the attenuation-pole frequencies.

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A New Hybrid Mode-Matching/Numerical Method for the Analysis of Arbitrarily Shaped Inductive Obstacles and Discontinuities in Rectangular Waveguides

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***Abstract*—A new and efficient hybrid mode-matching method is presented for the analysis of arbitrarily shaped inductive obstacles and/or discontinuities in a rectangular waveguide. The irregular region with obstacles and/or discontinuities is characterized using a full-wave hybrid spectral/numerical open-space technique expanding the fields in cylindrical wave functions. Next, a full-wave mode-matching procedure is used to match the cylindrical wave functions to guided modes in all ports and a generalized scattering matrix for the structure is finally obtained. The obstacles can be metallic or dielectric with complex permittivities and arbitrary geometries. The structure presents an arbitrary number of ports, each one with different orientation and dimensions. The accuracy of the method is validated comparing with results for several complex problems found in the literature. CPU times are also included to show the efficiency of the new method proposed.**

***Index Terms*—Microwave devices, mode-matching methods, spectral analysis, waveguide discontinuities.**

I. Introduction

Inductive obstacles and discontinuities in waveguiding structures have traditionally been a key element of many microwave devices, such as bandpass [1], [2] and band-stop [3] filters, post-coupled filters [3], [4], tapers [5], phase shifters [6], circulator elements [7], [8], rounded-corners effect [9], mitered bends [7], [10], [11], or manifold diplexers and multiplexers [12]. The correct analysis and design of these microwave devices is of great importance for many applications such as satellite and wireless communication systems [13]. Therefore, the analysis of inductive obstacles and discontinuities has recently received considerable attention in the technical literature [9], [11].

The existing methods for the analysis of the microwave devices just mentioned before fall into one of the three following categories:

1) analytical methods;
2) numerical methods;
3) hybrid methods.

The analytical or modal methods, such as those based on the generalized admittance matrix (GAM) method [14] or generalized scattering matrix (GSM) method [15], provide accurate and efficient results, but are only applicable to a few regularly shaped waveguide problems. On the other hand, the numerical or space discretization methods, such as the finite-element (FE) method [16], [17] or finite-difference time-domain (FDTD) method [18], are able to analyze problems with arbitrary geometries, but suffer from huge CPU time and storage requirements. An alternative to analytical and numerical methods is the combination of the main advantages of both types of techniques: the efficiency of modal methods and the flexibility of numerical methods. This is the aim of the so-called hybrid methods, which combine numerical and analytical techniques for the efficient analysis of a wide range of problems. A great number of hybrid techniques have been reported over the last years, with an increasing degree of flexibility. A combination of the moments method and the mode-matching technique

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