Electromagnetic Characterization of Tunable Bandpass Filters with a PET-controlled Perturber

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Abstract— Electromagnetic (EM) analysis is performed for a tunable bandpass filter with a magnetodielectric perturber controlled by an elastic piezoelectric transducer. The structure includes a perturber as a superstrate which consists of thin ferrite film with a high permeability and Rogers dielectric material with a high permittivity in a sandwich style. The structure is of multiscale feature because the thickness of the thin film is very small but cannot be ignored. The problem can be solved by surface integral equations (SIEs) in the integral equation approach, but the conditioning of system matrix may not be good. We use volume-surface integral equations to formulate the problem in this work and the disadvantage of pure SIEs can be overcome. A numerical example is presented to illustrate the approach.

1. INTRODUCTION

Tunable bandpass filters (BPFs) are vital microwave components and they have been widely used in communication systems. The design of tunable BPFs is challenging because they require a low loss and compact size. Recently, the tunable BPF with a magnetodielectric perturber controlled by an elastic piezoelectric transducer (PET) was developed and it looks very promising [1]. Such a tunable BPF uses a perturber as a superstrate touching on the microstrip and its position can be controlled by a PET. The perturber is made of a high-permeability ferrite film and a high-permittivity dielectric Rogers material in a sandwich style. The resonant frequency of the BPF can be tuned by applying different bias DC voltages to the PET or by using different layers of magnetodielectric sandwich. The tunable BPF can be easily fabricated with a compact size and low loss and its resonant frequency could be adjusted in a wide range.

Characterizing the tunability of the BPF relies on the electromagnetic modeling and analysis although a costly experimental method can be used. The structure is of multiscale characteristic because some dimensions are very small compared with others in geometry. Although the thickness of microstrip and ground may be ignored to simplify the analysis, the small thickness of high-permeability ferrite film cannot be ignored due to its significant influence and should be accounted for carefully [2]. The structure can be modelled by surface integral equations (SIEs) when all materials are assumed to be homogeneous [3], but the SIEs may not generate well-conditioned system matrices, especially for multiscale structures. Also, the SIEs need to use appropriate basis functions to represent the electric and magnetic current densities, respectively, in the method of moments (MoM) solution [4] and the choice of the basis functions or testing schemes could strongly affect the accuracy of solutions [5]. In this work, we use volume integral equations (VIEs) to describe the dielectric substrate and magnetodielectric perturber, and form volume-surface integral equations (VSIEs) after combining with the SIE governing the conducting microstrip and ground. The VIEs or VSIEs are usually more well-conditioned because they include the second-kind of integral equations [8]. We present a numerical example to demonstrate the analysis of the BPF and its effectiveness has been verified.

2. GOVERNING INTEGRAL EQUATIONS

The BPF structure includes both conducting microstrip and ground, dielectric substrate and Rogers material, and magnetic ferrite film. We assume that the microstrip and ground are perfectly electric conductors (PECs) with a negligible thickness and their EM feature can be described by the electric field integral equation (EFIE) when disregarding the coupling with other parts [3]

$$-\hat{n}\times\mathbf{E}^{ex}(\mathbf{r})=\hat{n}\times i\omega\mu_0\int_S\overline{\mathbf{G}}(\mathbf{r},\mathbf{r}')\cdot\mathbf{J}_S(\mathbf{r}')\,dS',\quad \mathbf{r}\in S \tag{1}$$

where $\mathbf{J}_S(\mathbf{r}')$ is the electric current density induced on the conductor surface S whose unit normal vector is $\hat{n}$ and $\mathbf{E}^{ex}(\mathbf{r})$ represents a delta-gap excitation at an appropriate position in a port. Also, $\overline{\mathbf{G}}(\mathbf{r},\mathbf{r}')$ is the dyadic Green's function defined by

$$\overline{\mathbf{G}}(\mathbf{r},\mathbf{r}') = \left(\bar{\mathbf{I}} + \frac{\nabla\nabla}{k_0^2}\right) g(\mathbf{r},\mathbf{r}') \tag{2}$$

where $\bar{\mathbf{I}}$ is the identity dyad, k_0 is the wavenumber of the free space with a permittivity ϵ_0 and a permeability μ_0, and $g(\mathbf{r},\mathbf{r}') = e^{ik_0R}/(4\pi R)$ is the scalar Green's function with $R = |\mathbf{r} - \mathbf{r}'|$ being the distance between an observation point $\mathbf{r}$ and a source point $\mathbf{r}'$. For homogeneous penetrable materials with a relative permittivity ϵ_r and a relative permeability μ_r, we can use the VIEs to catch up with the EM characteristic when disregarding the coupling with the conductors [3]

$$\mathbf{E}(\mathbf{r}) = \mathbf{E}^{ex}(\mathbf{r}) + i\omega\mu_0 \int_V \overline{\mathbf{G}}(\mathbf{r},\mathbf{r}') \cdot \mathbf{J}_V(\mathbf{r}')d\mathbf{r}' - \nabla \times \int_V \overline{\mathbf{G}}(\mathbf{r},\mathbf{r}') \cdot \mathbf{M}_V(\mathbf{r}')d\mathbf{r}', \quad \mathbf{r} \in V \tag{3}$$

$$\mathbf{H}(\mathbf{r}) = \mathbf{H}^{ex}(\mathbf{r}) + i\omega\epsilon_0 \int_V \overline{\mathbf{G}}(\mathbf{r},\mathbf{r}') \cdot \mathbf{M}_V(\mathbf{r}')d\mathbf{r}' + \nabla \times \int_V \overline{\mathbf{G}}(\mathbf{r},\mathbf{r}') \cdot \mathbf{J}_V(\mathbf{r}')d\mathbf{r}', \quad \mathbf{r} \in V \tag{4}$$

where $\mathbf{E}^{ex}(\mathbf{r}) = \mathbf{H}^{ex}(\mathbf{r}) = 0$ inside the materials and

$$\mathbf{J}_V\left(\mathbf{r}'\right) = i\omega\epsilon_0(1-\epsilon_r)\mathbf{E}\left(\mathbf{r}'\right) \tag{5}$$

$$\mathbf{M}_V\left(\mathbf{r}'\right) = i\omega\mu_0(1-\mu_r)\mathbf{H}\left(\mathbf{r}'\right) \tag{6}$$

are the volumetric electric and magnetic current densities inside the materials, respectively. When considering the coupling of fields produced by the current density on the conductors and the volume current densities inside the materials, we can form the following VSIEs

$$\begin{aligned} 0 = \ & \hat{n} \times \left[\mathbf{E}^{ex}(\mathbf{r}) + i\omega\mu_0 \int_S \overline{\mathbf{G}}(\mathbf{r},\mathbf{r}') \cdot \mathbf{J}_S(\mathbf{r}')\, dS' + i\omega\mu_0 \int_V \overline{\mathbf{G}}(\mathbf{r},\mathbf{r}') \cdot \mathbf{J}_V(\mathbf{r}')d\mathbf{r}' \right. \\ & \left. - \nabla \times \int_V \overline{\mathbf{G}}(\mathbf{r},\mathbf{r}') \cdot \mathbf{M}_V(\mathbf{r}')d\mathbf{r}'\right], \quad \mathbf{r} \in S \end{aligned} \tag{7}$$

$$\begin{aligned} \mathbf{E}(\mathbf{r}) = \ & i\omega\mu_0 \int_S \overline{\mathbf{G}}(\mathbf{r},\mathbf{r}') \cdot \mathbf{J}_S(\mathbf{r}')\, dS' + i\omega\mu_0 \int_V \overline{\mathbf{G}}(\mathbf{r},\mathbf{r}') \cdot \mathbf{J}_V(\mathbf{r}')d\mathbf{r}' \\ & -\nabla \times \int_V \overline{\mathbf{G}}(\mathbf{r},\mathbf{r}') \cdot \mathbf{M}_V(\mathbf{r}')d\mathbf{r}', \quad \mathbf{r} \in V \end{aligned} \tag{8}$$

$$\begin{aligned} \mathbf{H}(\mathbf{r}) = \ & -\frac{1}{2}\hat{n} \times \mathbf{J}_S(\mathbf{r}') + \fint_S \nabla g(\mathbf{r},\mathbf{r}') \times \mathbf{J}_S(\mathbf{r}') + i\omega\epsilon_0 \int_V \overline{\mathbf{G}}(\mathbf{r},\mathbf{r}') \cdot \mathbf{M}_V(\mathbf{r}')d\mathbf{r}'\, dS' \\ & +\nabla \times \int_V \overline{\mathbf{G}}(\mathbf{r},\mathbf{r}') \cdot \mathbf{J}_V(\mathbf{r}')d\mathbf{r}', \quad \mathbf{r} \in V \end{aligned} \tag{9}$$

from which the unknown current densities can be solved and the frequency characteristic of the structure can then be found.

3. METHOD OF MOMENTS (MOM) SOLUTION

The above VSIEs can be solved by the MoM in which the surface current density on the conductors is expanded by the Rao-Wilton-Glisson (RWG) basis function [6] while the electric flux density and magnetic flux density inside the materials are represented with the Schaubert-Wilton-Glisson (SWG) basis function [7], i.e.,

$$\mathbf{J}_S(\mathbf{r}') = \sum_{n=1}^{N_c} J_n \mathbf{e}_n(\mathbf{r}') \tag{10}$$

$$\mathbf{D}(\mathbf{r}') = \sum_{n=1}^{N_d} D_n \mathbf{f}_n(\mathbf{r}') \tag{11}$$

$$\mathbf{B}(\mathbf{r}') = \sum_{n=1}^{N_d} B_n \mathbf{f}_n(\mathbf{r}') \tag{12}$$

where $\mathbf{e}_n(\mathbf{r}')$ is the RWG basis function and N_c is the number of RWG triangle pairs while $\mathbf{f}_n(\mathbf{r}')$ is the SWG basis function and N_d is the number of SWG tetrahedron pairs. Also, J_n, D_n, and B_n are the expansion coefficients for the current densities, respectively. The flux densities are related to the current densities inside the materials through $\mathbf{D}(\mathbf{r}') = \epsilon_0\epsilon_r\mathbf{E}(\mathbf{r}')$ and $\mathbf{B}(\mathbf{r}') = \mu_0\mu_r\mathbf{H}(\mathbf{r}')$, respectively, i.e.,

$$\mathbf{J}_V(\mathbf{r}') = i\omega\kappa_\epsilon\mathbf{D}(\mathbf{r}') \tag{13}$$
$$\mathbf{M}_V(\mathbf{r}') = i\omega\kappa_\mu\mathbf{B}(\mathbf{r}') \tag{14}$$

where $\kappa_\epsilon = \frac{1}{\epsilon_r} - 1$ and $\kappa_\mu = \frac{1}{\mu_r} - 1$ are the contrast ratio of permittivity and permeability, respectively. The above VSIEs can be transformed into a matrix equation by using the RWG and SWG basis functions as testing functions to test corresponding equations, respectively. By doing so, we can obtain the following matrix equation

$$\begin{aligned} -\left\langle \mathbf{e}_m(\mathbf{r}), \frac{\mathbf{E}^{ex}(\mathbf{r})}{i\omega\mu_0} \right\rangle &= \sum_{n=1}^{N_c} J_n\langle \mathbf{e}_m(\mathbf{r}), \overline{\mathbf{G}}(\mathbf{r},\mathbf{r}'), \mathbf{e}_n(\mathbf{r}')\rangle \\ &\quad + \sum_{n=1}^{N_d} D_n\langle \mathbf{e}_m(\mathbf{r}), \overline{\mathbf{G}}_0(\mathbf{r},\mathbf{r}'), \mathbf{f}_n(\mathbf{r}')\rangle, \quad m = 1,2,\ldots,N_c \end{aligned} \tag{15}$$

$$\begin{aligned} D_m\left\langle \mathbf{f}_m(\mathbf{r}), \frac{\mathbf{f}_m(\mathbf{r})}{i\omega\mu_0\epsilon(\mathbf{r})} \right\rangle &= \sum_{n=1}^{N_c} J_n\langle \mathbf{f}_m(\mathbf{r}), \overline{\mathbf{G}}(\mathbf{r},\mathbf{r}'), \mathbf{e}_n(\mathbf{r}')\rangle \\ &\quad + \sum_{n=1}^{N_d} D_n\langle \mathbf{f}_m(\mathbf{r}), \overline{\mathbf{G}}_0(\mathbf{r},\mathbf{r}'), \mathbf{f}_n(\mathbf{r}')\rangle, \quad m = 1,2,\ldots,N_d \end{aligned} \tag{16}$$

$$\begin{aligned} D_m\left\langle \mathbf{f}_m(\mathbf{r}), \frac{\mathbf{f}_m(\mathbf{r})}{i\omega\mu_0\epsilon(\mathbf{r})} \right\rangle &= \sum_{n=1}^{N_c} J_n\langle \mathbf{f}_m(\mathbf{r}), \overline{\mathbf{G}}(\mathbf{r},\mathbf{r}'), \mathbf{e}_n(\mathbf{r}')\rangle \\ &\quad + \sum_{n=1}^{N_d} D_n\langle \mathbf{f}_m(\mathbf{r}), \overline{\mathbf{G}}_0(\mathbf{r},\mathbf{r}'), \mathbf{f}_n(\mathbf{r}')\rangle, \quad m = 1,2,\ldots,N_d \end{aligned} \tag{17}$$

where $\overline{\mathbf{G}}_0(\mathbf{r},\mathbf{r}') = -i\omega\kappa(\mathbf{r}')\overline{\mathbf{G}}(\mathbf{r},\mathbf{r}')$. The above matrix equation can be solved with a matrix solver so that the unknown current density and flux density can be found.

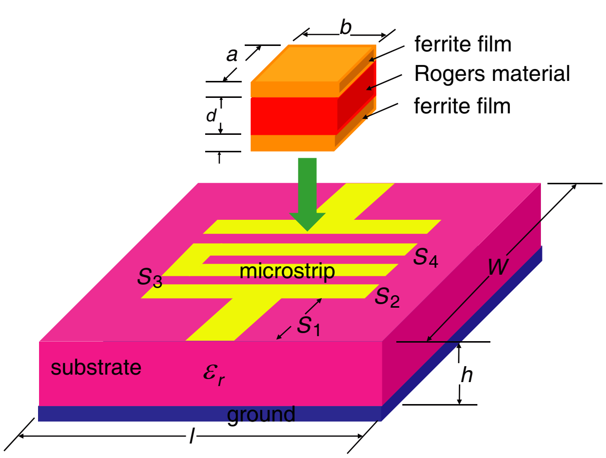

Figure 1: Geometry of a tunable BPF with a magnetodielectric perturber consisting of ferrite film and Rogers material in a sandwich style.

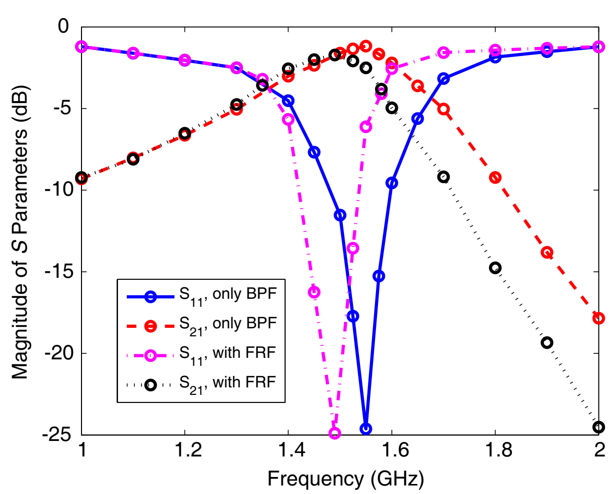

Figure 2: S parameters of a tunable BPF with a magnetodielectric perturber consisting of ferrite film and Rogers material in a sandwich style.

4. NUMERICAL EXAMPLE

We present a numerical example to demonstrate the approach. A tunable BPF as shown in Figure 1 is considered and the geometry is defined by $l = 22.0$, $w = 20.26$, $h = 1.28$, $s_1 = 9.0$, $s_2 = 0.23$, $s_3 = 0.07$, $s_4 = 1.2$, $d = 0.254$, $t = 0.01$, $a = 20$, and $b = 10$, all in millimeter (mm). The substrate and Rogers material of the perturber have a relative permittivity $\epsilon_r = 10.2$ and a relative permeability $\mu_r = 1.0$ while the relative permittivity and permeability of the ferrite film are $\epsilon_r = 13.0$ and $\mu_r = 10.0$, respectively. Figure 2 shows the solutions of S parameters (magnitude) for the structure with or without the perturber and the results are close to the experimental results as shown in [1].

5. CONCLUSION

In this work, we address the EM analysis for a tunable BPF structure which includes a PET-controlled perturber with a high-permittivity Rogers material and high-permeability thin ferrite film in a sandwich style. Although the problem can be solved by pure SIEs with an assumption of homogeneous penetrable materials, we use the VSIE to solve it instead. Compared the SIEs, the VSIEs can usually result in a well-conditioned system matrix with the regular basis functions and testing scheme. A typical numerical example has been presented to demonstrate the effectiveness of the approach.

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REFERENCES

1. Yang, G.-M., O. Obi, G. Wen, and N. X. Sun, "Design of tunable bandpass filters with ferrite sandwich materials by using a piezoelectric transducer," *IEEE Trans. Magn.*, Vol. 47, No. 10, 3732–3735, Oct. 2011.
2. Yang, G.-M., X. Xing, A. Daigle, M. Liu, O. Obi, J. W. Wang, K. Naishadham, and N. X. Sun, "Electronically tunable miniaturized antennas on magnetoelectric substrates with enhanced performance," *IEEE Trans. Magn.*, Vol. 44, No. 11, 3091–3094, Nov. 2008.
3. Chew, W. C., M. S. Tong, and B. Hu, *Integral Equation Methods for Electromagnetic and Elastic Waves*, Morgan & Claypool, San Rafael, CA, 2008.
4. Harrington, R. F., *Field Computation by Moment Methods*, Macmillan, New York, 1968.
5. Tong, M. S., "Efficient electromagnetic analysis for interconnect and packaging structures using dual basis function in the method of moments," *IEEE Trans. Compon., Packag., Manuf. Technol.*, Vol. 1, No. 7, 1089–1097, Jul. 2011.
6. Rao, S. M., D. R. Wilton, and A. W. Glisson, "Electromagnetic scattering by surfaces of arbitrary shape," *IEEE Trans. Antennas Propagat.*, Vol. 30, 409–418, 1982.
7. Schaubert, D. H., D. R. Wilton, and A. W. Glisson, "A tetrahedral modeling method for electromagnetic scattering by arbitrary shaped inhomogeneous dielectric bodies," *IEEE Trans. Antennas Propagat.*, Vol. 32, No. 1, 77–85, 1984.
8. Usner, B. C., K. Sertel, M. A. Carr, and J. L. Volakis, "Generalized volume-surface integral equation for modeling inhomogeneities within high contrast composite structures," *IEEE Trans. Antennas Propagat.*, Vol. 54, No. 1, 68–75, Jan. 2006.