

Microstrip Lowpass Filters with Reduced Size and Improved Stopband Characteristics

Zhewang MA^{†a)}, Kaneo NOMIYAMA[†], Members, and Yoshio KOBAYASHI[†], Fellow

SUMMARY Novel microstrip lowpass filters are developed with reduced size and significantly improved stopband characteristics. After introducing quarter-wavelength open stubs, we get one or two transmission zeros in the stopband. By folding the high impedance microstrip lines, we reduce the size of the filter. Three-pole and five-pole lowpass filters are designed, and their measured frequency responses agree well with theoretical predictions.

key words: lowpass filters, microstrip lines, open stubs, stepped-impedance, transmission zeros

1. Introduction

Small-sized and high-performance RF/microwave planar filters are demanded in many applications. Among microstrip lowpass filters (LPFs), stepped-impedance L - C ladder type lowpass filters are most widely used. Short lengths of high and low impedance microstrip lines are cascaded alternately to approximate lumped L - C ladder type lowpass filters [1], [2].

The microstrip stepped-impedance lowpass filter is simple in structure and easy to design. On the other hand, it suffers from a number of apparent shortcomings. First, it is large in size, usually too long in length. Second, its stopband response is poor, with much smaller attenuation than predicted by its prototype filter. Third, a high impedance line may result in inordinate demand of fabrication tolerance.

There are a number of methods to improve the stopband characteristics of LPFs. For example, we can use a higher order degree filter, which will, however, result in a bigger circuit size and a larger insertion loss. We can also choose designing an elliptic or quasi-elliptic function LPF by inserting parallel-resonators in the series branches of a LPF, or series-resonators in the shunt branches. However, the design formulas, if available, are more complicated than those for maximally flat or Chebyshev response filters [2]. Finally, we can try to produce transmission zeros by introducing cross-couplings between non-adjacent reactive elements in a LPF. Levy developed an approximate synthesis method for a LPF having a pair of transmission zeros [3]. Hong improved that method by providing some more accurate tables and formulas that were obtained by curve fitting [4]. Their method is simple and useful in many cases, but is

feasible only for filters with a even number of resonators.

In this paper, a novel microstrip lowpass filter with reduced size and improved stopband characteristics is proposed. By introducing one or two quarter-wavelength open stubs at the input and/or output of the filter, we produce one or two transmission zeros at desired frequencies in the stopband, and therefore obtain a sharp rate of cutoff and greatly increased attenuation. The high impedance lines are folded, and hence the length of the filter is reduced significantly. This is particularly true in the case of a higher degree of filter.

The idea of using quarter-wavelength open stubs to produce transmission zeros can be found in some previous papers. For example, [5] and [6] discussed how to use tapped half-wavelength coplanar waveguide (CPW) resonators to get multiple transmission zeros and hence improve the skirt characteristics of a filter. The discussions were made for CPW bandpass filters. Therefore, both the structure and the design method of the filter are mostly different with those of this work which deals with microstrip lowpass filters.

In section 2, a three-pole microstrip lowpass filter with conventional stepped-impedance layout is designed and measured first for later comparison. Next, our newly developed three-pole and five-pole lowpass filters are described, including their design process and measurement evaluation. It is shown that the measured filtering characteristics of the designed filters agree well with theoretical predictions.

2. Filter Design and Measurements

A three-pole Chebyshev response lowpass filter is considered first. The specifications are: cutoff frequency $f_c=2.5$ GHz, passband ripple 0.1 dB, source and load impedance $Z_0=50\ \Omega$. The L - C ladder type circuit of the lowpass filter is shown in Fig. 1, where the values of L and C elements are determined by using the well-known formulas in [1], together with the above specifications.

The filter is realized first by using the conventional microstrip stepped-impedance layout shown in Fig. 2. A commercial substrate (MCL-E-67) with a relative dielectric constant of 4.23, loss tangent of 0.025 at 2 GHz, and thickness of 1.20 mm is used. The strip width of the input/output feed lines is chosen as 2.2 mm, to get a characteristic impedance of 50 Ω .

The L and C elements in Fig. 1 are realized by using

Manuscript received May 6, 2004.

Manuscript revised August 16, 2004.

[†]The authors are with the Department of Electrical and Electronic Systems, Saitama University, Saitama-shi, 338-8570 Japan.

a) E-mail: ma@ees.saitama-u.ac.jp

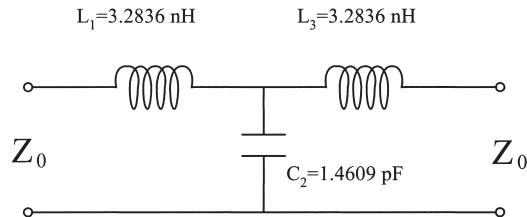


Fig. 1 L-C ladder type circuit of a three-pole lowpass filter.

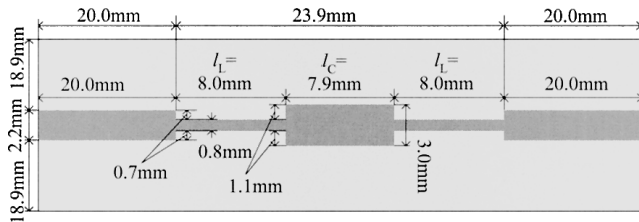


Fig. 2 Layout of a 3-pole lowpass filter using stepped-impedance microstrip lines.

high and low impedance microstrip lines, respectively. A very high impedance results in a very narrow line width, which in turn requires a critical fabrication tolerance. In order to avoid the cost of high-precision fabrication, the width of the high impedance line in this work is chosen as 0.8 mm. The width of the low impedance line is chosen as 3.0 mm.

The initial lengths of the high and low impedance lines are found by using the following approximate formulas [2]:

$$\begin{aligned} \omega_c L &= Z_{oL} \sin\left(\frac{2\pi l_L}{\lambda_{gL}}\right) + Z_{oC} \tan\left(\frac{\pi l_C}{\lambda_{gC}}\right) \\ \omega_c C &= \frac{1}{Z_{oC}} \sin\left(\frac{2\pi l_C}{\lambda_{gC}}\right) + 2 \frac{1}{Z_{oL}} \tan\left(\frac{\pi l_L}{\lambda_{gL}}\right) \end{aligned} \quad (1)$$

where L and C are the reactive element values shown in Fig. 1, l_L and l_C are the lengths of the high and low impedance lines shown in Fig. 2, λ_{gL} and λ_{gC} are the guided wavelengths, and Z_{oL} and Z_{oC} are the characteristic impedances of these L - and C -lines, respectively.

With the initial dimensions of the LPF, the filtering characteristics are then simulated by using Sonnet em [7], a commercial electromagnetic (EM) solver based on the moment method. In most cases, it is found that the passband response of the LPF does not satisfy the required specifications. In order to improve the passband response of the filter, we need to make adjustment of the dimensions of the filter. In the case of the 3-pole LPF, we have two parameters, the lengths l_L and l_C of the high and low impedance lines shown in Fig. 2, to be varied. The adjustment of l_L and l_C can be done using the parameter-sweep option of Sonnet em to get a satisfactory passband response. This is an EM-based optimization of the filter's geometrical parameters, which can be employed when the number of parameter variables is small and the EM computation time is endurable.

Another computationally more effective optimization method is the circuited-based approach [8], which can be

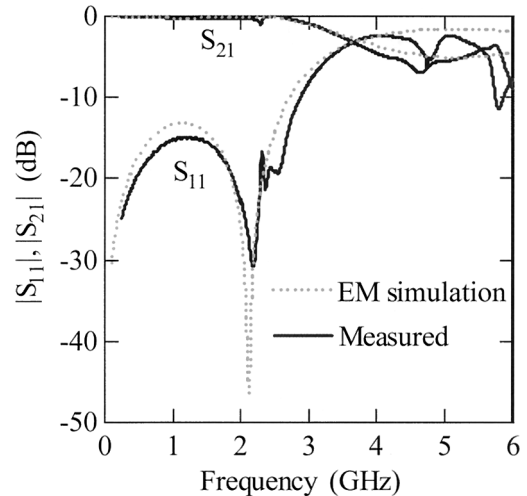


Fig. 3 Simulated and measured frequency response of the 3-pole lowpass filter using stepped-impedance microstrip lines.

implemented, for example, by using ADS, a circuit analysis simulator [9]. Referring to the equivalent circuit in Fig. 1, we see that there are two parameters (or say variables), L and C , to be adjusted. We choose the ideal frequency response, $S_{11}(f)$ and $S_{21}(f)$, as the initial function, and the EM-simulated response, $S'_{11}(f)$ and $S'_{21}(f)$, as the target function. Then we minimize the following error function, which represents the difference between the initial function and the target function, by using an optimization algorithm [8].

$$\begin{aligned} Error(L, C) &= \sum_{n=1}^N \left\{ \left[|S_{11}(f_n)| - |S'_{11}(f_n)| \right]^2 \right. \\ &\quad \left. + \left[|S_{21}(f_n)| - |S'_{21}(f_n)| \right]^2 \right\} \end{aligned} \quad (2)$$

Here f_n is the sample frequency, N is the number of samples in the passband of the filter. As a result of the optimization, the detuned values of the L - and C - parameters are found, from which the lengths, l_L and l_C , of the high and low impedance lines are adjusted.

The final geometrical dimensions of the three-pole filter are shown in Fig. 2. The designed filter is fabricated and its measured frequency response is shown in Fig. 3 by solid lines. The dotted lines in Fig. 3 are the simulated results by Sonnet em, and they agree well with the measured ones. The unexpected dents in the measured curves are caused by some mismatch between the filter's input/output lines and the feeding SMA connectors of our test fixture.

Fig. 3 shows that the stopband response of the conventional stepped-impedance microstrip lowpass filter is very poor. The attenuations in the stopband do not fall to values as large as predicted by the lumped-element circuit in Fig. 1.

In order to obtain a sharper rate of cutoff and larger attenuations in the stopband, it is desirable to introduce transmission zeros at finite frequencies in the stopband. As mentioned in the Introduction, for the 3-pole filter shown in

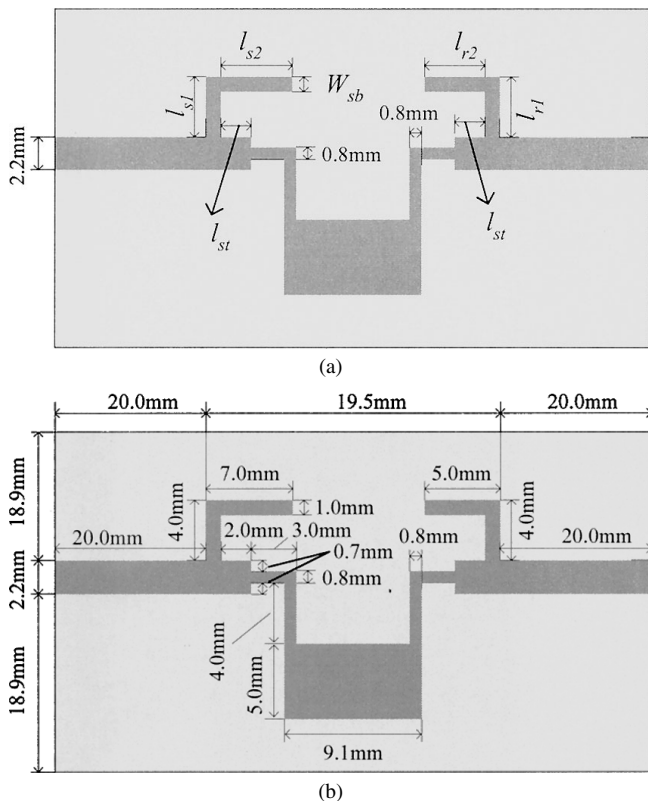


Fig. 4 (a) Layout of the proposed 3-pole lowpass filter. Quarter-wavelength open stubs are introduced at the input and output to produce two transmission zeros in the stopband. (b) Dimension of the filter after the design.

Fig. 1, one method is to design an elliptic function filter by replacing the shunt C_2 element with a series L - C resonator. Another method usually used is to introduce some cross-coupling between L_1 and L_3 to produce one transmission zero at a desired frequency in the stopband [2], [10].

We propose here a novel and easy to implement method to produce one or two transmission zeros to improve the stopband characteristics of a lowpass filter. Take the filter in Fig. 1 as an example, the structure of our new filter is shown in Fig. 4(a). We use also short lengths of high and low impedance lines to approximate lumped L and C elements in Fig. 1. The high impedance lines are bent to the lower side of the input/output lines. At the upper side, quarter-wavelength open stubs are introduced, one is connected to the input, and the other to the output, to produce two transmission zeros in the stopband.

The design of this filter includes mainly three steps. First, the initial lengths of the high and low impedance lines are determined in a similar way described above for the stepped-impedance LPF in Fig. 2, using the approximate formulas (1).

Second, the lengths l_{sb1} and l_{sb2} of the open stubs are chosen as

$$\begin{aligned} l_{sb1} &= l_{s1} + l_{s2} = \lambda_{g1}/4 \\ l_{sb2} &= l_{r1} + l_{r2} = \lambda_{g2}/4 \end{aligned} \quad (3)$$

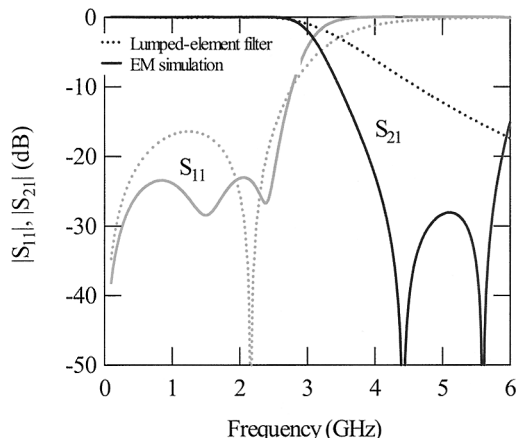


Fig. 5 Comparison of simulated responses of the filter in Fig. 4. The solid lines are computed by Sonnet em, and the dotted lines from the lumped-element circuit in Fig. 1.

here λ_{g1} and λ_{g2} are guided wavelengths of the open stubs at frequencies f_{p1} and f_{p2} , respectively, where the desired transmission zeros occur. The strip width W_{sb} of the open stubs is arbitrary, and is chosen as 1.0mm here. The connecting positions of the open stubs with the input/output are chosen close to the high impedance lines. In this example, l_{st} is chosen as 2.0mm . However, it is worth to note that our simulation results reveal that the frequency response of the filter is not sensitive to the variation of l_{st} . When l_{st} is changed from 2.5mm to 2.0mm , and then to 1.5mm , the simulated frequency response curves of the filter varied so little that they can be hardly discriminated from each other in the same figure.

Moreover, it should be noted that the positions of the two transmission zeros in the stopband can be moved separately by changing the lengths of the left and right open stubs in Fig. 4(a). If we need only one transmission zero, we can use only one open stub at either the input or output of the LPF.

The final step of the design is to make appropriate adjustment of the lengths of the high and low impedance lines to get desired passband response of the filter. The adjustment process is the same as that described above for the stepped-impedance LPF. We can use either a circuit-based optimization, or an EM-based optimization. We can even combine both of these optimization processes. The final geometrical dimensions of the filter are shown in Fig. 4.(b).

Fig. 5 provides a comparison of the filter responses. The solid lines are the simulated results of the filter in Fig. 4(b) using Sonnet em, and the dotted lines are computed based on the lumped-element circuit in Fig. 1. As expected, the new filter owns two transmission zeros at about 4.4 and 5.6GHz , respectively, and shows greatly increased attenuations in the stopband.

The filter designed above is fabricated using the MCL-E-67 substrate. In Fig. 6, the measured frequency response (solid line) is compared with the simulated one (dotted line by Sonnet em), and a good agreement is found. As ex-

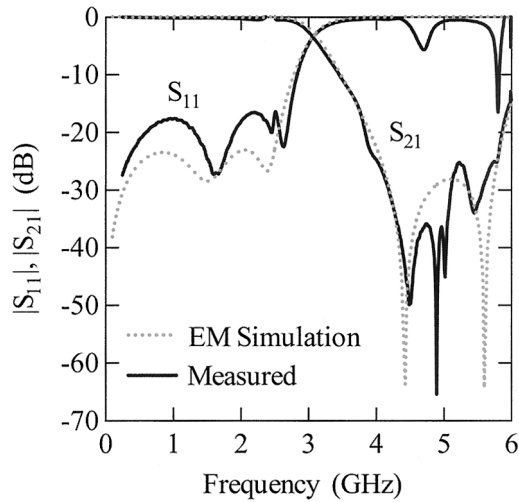


Fig. 6 Comparison of measured and simulated responses of the 3-pole filter in Fig. 4. The solid and dotted lines are measured and simulated results, respectively.

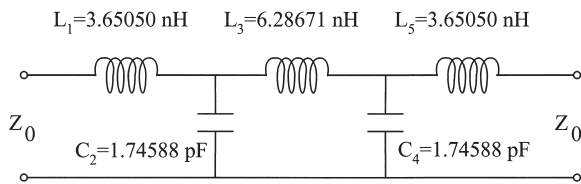


Fig. 7 L-C ladder type circuit of a five-pole lowpass filter.

plained above for Fig. 3, the dents in the measured curves are caused by some mismatch between the input/output of the filter and the feeding SMA connectors of our test fixture. In our next five-pole filter example, narrower input/output microstrip lines are used, and the mismatch between the input/output of the filter and the feeding ports of the test fixture is removed. As a result, smooth measurement curves are obtained as shown later.

The spurious passband in Fig. 5 and 6 begin to occur at about 6 GHz. This spurious passband can be moved away up to higher frequencies if higher characteristic impedance is used for the inductive lines in Fig. 4.

The MCL-E-67 substrate is a cheap and lossy substrate (loss tangent 0.025 at 2 GHz). However, the measured passband insertion loss in Fig. 6 is quite small. The result encourages us to use this type of cheap substrate to develop high performance lowpass filters at low costs.

Next, a five-pole Chebyshev response lowpass filter is developed. We try to use another type of commercial substrate R-4728. This substrate has a relative dielectric constant of 10.2, loss tangent of 0.004 at 2 GHz, and thickness of 0.78 mm. The design specifications are the same as those of the three-pole filter above. The lumped-element L-C circuit of the filter is given in Fig. 7.

The proposed microstrip structure of the five-pole filter is shown in Fig. 8. The high impedance lines are folded into meander lines, thus the overall length of the filter is re-

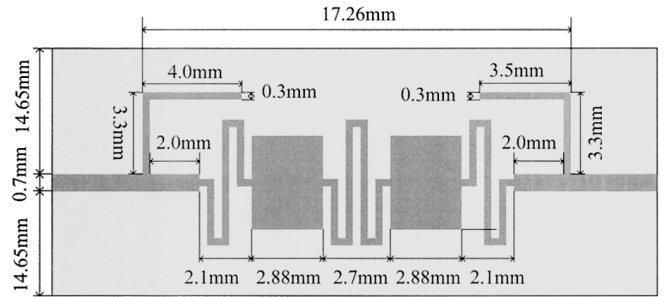


Fig. 8 Layout of the proposed 5-pole lowpass filter. Quarter-wavelength open stubs are introduced at the input and output to produce two transmission zeros in the stopband. The high impedance lines are folded into meander lines to reduce the length of the filter.

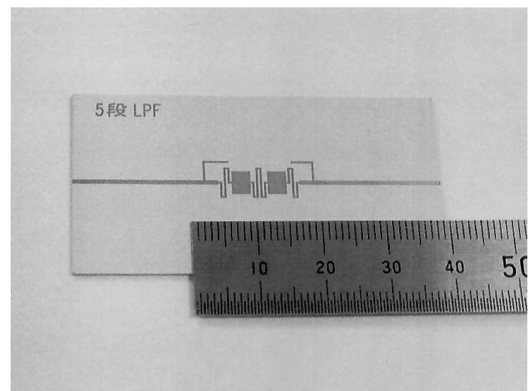


Fig. 9 Photograph of the fabricated 5-pole lowpass filter.

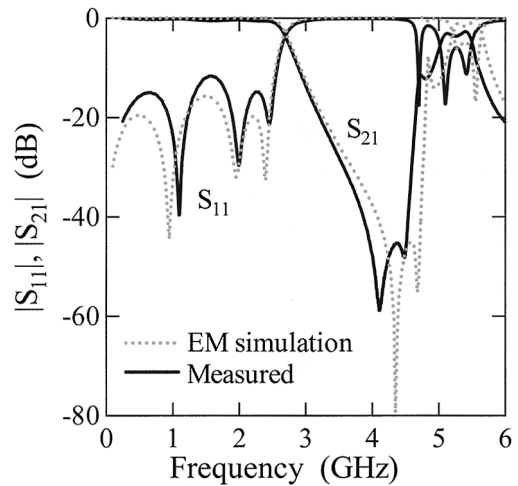


Fig. 10 Comparison of measured and simulated responses of the 5-pole filter. The solid and dotted lines are measured and simulated results, respectively.

duced significantly. The strip width of the input/output line is 0.7 mm, which corresponds to a characteristic impedance of 50 Ω. The strip widths of the high impedance lines and the open stubs are 0.3 mm. The filter is designed following the procedure of the three-pole filter described above.

Fig. 9 is a photograph of the fabricated five-pole low-

pass filter. In Fig. 10, the measured frequency response (solid line) is compared with the simulated one (dotted line by Sonnet em), and a good agreement is observed. At about 4.1 and 4.5 GHz, two transmission zeros occurred due to the quarter-wavelength open stubs at the input and output of the filter. As a result, a sharp rate of cutoff is realized near the passband. The passband insertion loss is also found to be very small.

The spurious passband in Fig. 10 occurs around 5 GHz. This spurious passband can be moved away up to higher frequencies if higher characteristic impedance is used for the inductive lines in the filter.

3. Conclusions

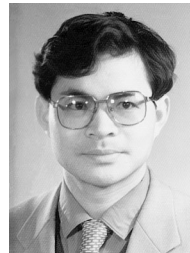
Three-pole and five-pole microstrip lowpass filters are developed successfully with reduced size and improved stopband characteristics. While the size reduction is accomplished by folding the high impedance lines, the improvement in frequency characteristics is realized by introducing quarter-wavelength open stubs, which in turn produce transmission zeros in the stopband. The filter is easy to design, and the positions of the transmission zeros are easy to control. The described methods can also be employed in the design of other types of RF/microwave filters.

Acknowledgments

The authors would like to thank Mr. G. Hagiwara of Link-Circuit Inc., and Mr. T. Kawaguchi of Saitama University for their assistance and support in this work. This work is also supported in part by NSFC (GP60271029).

References

- [1] G.L. Matthaei, L. Young, and E.M.T. Jones, *Microwave Filters, Impedance-Matching Networks, and Coupling Structures*, McGraw-Hill, New York, 1964.
- [2] J.S. Hong and M.J. Lancaster, *Microstrip Filters for RF/Microwave Applications*, pp.17–19, John Wiley & Sons, New York, 2001.
- [3] R. Levy, "Filters with single transmission zeros at real and imaginary frequencies," *IEEE Trans. Microw. Theory Tech.*, vol.MTT-24, no.4, pp.172–181, April 1976.
- [4] J.S. Hong and M.J. Lancaster, "Design of highly selective microstrip bandpass filters with a single pair of attenuation poles at finite frequencies," *IEEE Trans. Microw. Theory Tech.*, vol.MTT-48, no.7, pp.1098–1107, July 2000.
- [5] K. Wada and I. Awai, "Basic characteristics of a quarter-wavelength CPW resonator with tap-feed structure and its application to a bandpass filter with attenuation poles," *IEICE Trans. Electron.*, vol.E81-C, no.6, pp.924–933, June 1998.
- [6] K. Wada and I. Awai, "Design of a bandpass filter with multiple attenuation poles based on tapped resonators," *IEICE Trans. Electron.*, vol.E82-C, no.7, pp.1116–1122, July 1999.
- [7] Sonnet Suite, Ver.8.0, Sonnet Software, Liverpool, NY, 2002.
- [8] Z. Ma, H. Suzuki, and Y. Kobayashi, "Design and diagnosis of a 5 GHz 10-pole HTS bandpass filter using CPW quarter-wavelength resonators," *IEICE Trans. Electron.*, vol.E86-C, no.2, pp.144–149, Feb. 2003.
- [9] Agilent ADS2002, Agilent Technologies, Palo Alto, CA, 2002.
- [10] Z. Ma, T. Asano, and Y. Kobayashi, "Theory for the design of a filter having one cross coupling path to realize transmission zeros," *IEICE Trans. Electron.*, vol.E86-C, no.8, pp.1690–1698, Aug. 2003.



Zhewang Ma was born in Anhui, China, on July 7, 1964. He received the B.Eng. and M.Eng. degrees from the University of Science and Technology of China (USTC), Hefei, China, in 1986 and 1989, respectively. In 1995, he was granted the Dr. Eng. degree from the University of Electro-Communications, Tokyo, Japan. He was a Research Assistant in 1996, in the Department of Electronic Engineering, the University of Electro-Communications, and became an Associate Professor there in 1997. Since 1998,

he has been an Associate Professor in the Department of Electrical and Electronic Systems, Saitama University, Japan. From 1985 to 1989, he was engaged in research works on dielectric waveguides, resonators and leaky-wave antennas. From 1990 to 1997, he did studies on computational electromagnetics, analytical and numerical modeling of various microwave and millimeter wave transmission lines and circuits. His current research works are mainly on the design of microwave and millimeter wave filters, measurements of dielectric materials and high temperature superconductors. He received Japanese Government (Ministry of Education, Culture, Sports, Science and Technology) Graduate Scholarship from 1991 to 1993. He was granted the URSI Young Scientist Award in 1993. From 1994 to 1996, he was a Research Fellow of the Japan Society for the Promotion of Science (JSPS). Dr. Ma is a member of IEEE. He has served on the Editorial Board of *IEEE Transactions on Microwave Theory and Techniques*, Review Board of *IEEE Microwave and Wireless Components Letters*, and Review Board of *IEICE Transactions on Electronics*, Japan. He was a member of the Steering Committee for 2002 Asia Pacific Microwave Conference (APMC2002) held in Kyoto, Japan.



Kaneo Nomiya was born in Fukuoka, Japan, in 1979. He received B.E. and M.E. degrees in electrical engineering from Saitama University, Japan, in 2001 and 2003, respectively. He has been engaged in the design of microwave planar filters.



Yoshio Kobayashi was born in Japan on July 4, 1939. He received the B.E., M.E., and D.Eng. Degrees in electrical engineering from Tokyo Metropolitan University, Tokyo, Japan, in 1963, 1965, and 1982, respectively. Since 1965, he has been with Saitama University, Saitama, Japan. He is now a professor at the same university. His current research interests are in dielectric resonators and filters, measurements of low-loss dielectric and high-temperature superconductive (HTS) materials, and HTS filters,

in microwave and millimeter wave region. He served as the Chair of the Technical Group on Microwaves, IEICE, from 1993 to 1994, as the Chair of the Technical Group of Microwave Simulators, IEICE, from 1995 to 1997, as the Chair of Technical Committee on Millimeter-wave Communications and Sensing, IEE Japan, from 1993 to 1995, as the Chair of Steering Committee, 1998 Asia Pacific Microwave Conference (APMC'98) held in Yokohama, as the Chair of the National Committee of APMC, IEICE from 1999 to 2000, and as the Chair of the IEEE MTT-S Tokyo Chapter from 1995 to 1996. He also serves as a member of the National Committee of IEC TC49 since 1991, the Chair of the National Committee of IEC TC49 WG10 since 1999 and a member of the National Committee of IEC TC90 WG8 since 1997. Prof. Kobayashi received the Inoue Harushige Award on "Dielectric filters for mobile communication base stations" in 1995. He is a Fellow of IEEE and a member of IEE Japan.