A Compact Second-Order LTCC Bandpass Filter With Two Finite Transmission Zeros

Lap Kun Yeung, *Student Member, IEEE*, and Ke-Li Wu, *Senior Member, IEEE*

***Abstract*—A novel implementation and associated design formula for a compact low-temperature cofired ceramics (LTCC) lumped-element second-order bandpass filter are proposed in this paper. The filter schematic that provides two finite transmission zeros is well known. It is shown in the paper that the filter schematic is built on a pair of conventional inductive coupled resonator tanks with a feedback capacitor between input and output. While revealing its working mechanism both graphically and mathematically, a simple design procedure for such a compact filter is also given. The proposed filter has been implemented in a six-layer ceramic substrate using LTCC technology, showing promising application potentials in miniaturized mobile terminals and Bluetooth RF front-ends. The measured results agree very well with the full-wave electromagnetic designed responses.**

***Index Terms*—Filters, low-temperature cofired ceramics (LTCC), multilayer RF circuits.**

I. Introduction

THE latest wireless products demand ever-greater functionality, higher performance, and lower cost in smaller and lighter formats. This demand has been satisfied to date by major advances in integrated circuit (IC) and high-density packaging technologies, even though the RF sections have continued to demand high-performance and miniaturized passive components such as matching and filtering circuitry. Continuing reductions in size of discrete surface mounted components are having diminishing returns because of the incompatibility of the printed circuit board (PCB) technology, as well as the high cost of assembly of those tiny discrete components. Therefore, new technological approaches are required to address the integration of passives. One of the important means today for integrating passives, particularly for RF functional passive modules, is low-temperature cofired ceramics (LTCC).

Thanks to the new technology that has the greatest ever flexibility to layout conducting circuitry in a three-dimensional fashion, many new compact passive circuit implementations, which were considered impossible to realize with traditional processes, have been proposed for various wireless applications. Examples of the applications include the compact semilumped low-pass filter in [1] and the LTCC duplexers in [2] and [3]. It has been reported recently that a RF front-end module (FEM), integrating over 50 components in a package measuring only 6.7 $\times$ 5.5 $\times$ 1.8 mm^3, for global system for mobile (GSM) triple-band mobile phones has been built based on LTCC technology [4].

Among various passive components, people usually pay the most attention to the filter. With the added new design dimension in the z-direction provided by LTCC, a lumped-element RF filter can now be implemented in a stacked structure. The stacked architecture can not only shrink the size, but also provide various coupling mechanisms to achieve a better selectivity. A notable bandpass-filter structure that truly utilizes the LTCC features is presented in [5], where a mutual inductive coupling was achieved by overlapping the two inductor strips in the z-direction. The inductive mutual coupling is equivalent to inserting, in series, an *LC* resonator tank between the two resonators. Therefore, one finite transmission zero can be introduced to improve the selectivity at the image frequency.

In this paper, a compact LTCC lumped-element structure for a well-known second-order filter schematic [6], [7] with two transmission zeros is proposed. This filter has the same number of elements as the one in [5]. However, rather than having a coupling capacitor between the two resonators, this capacitor is now moved to connect the input and output [see Fig. 1(a)] to create a feedback path. It is shown that this change will introduce two finite zeros, instead of one, to the transmission response of the filter. The transmission zeros improve the filter selectivity by trading off the attenuation at the far ends of both the lower and upper stopbands.

The emphasis of this paper is also placed on revealing the working mechanism of the filter schematic both graphically and mathematically. A simple design procedure for such a compact filter is also given. The graphic solution suggests that the presence of the zeros (as long as they are not too close to the passband) do not change the passband characteristics of the filter too much, whereas the mathematical solution points out that the filter can be readily designed with the traditional filter synthesis procedure. A prototype filter of size 176 $\times$ 80 $\times$ 21.6 mil^3 has been implemented in a multilayer LTCC substrate for experimental verification. The filter components have been realized using 7-μm-thick silver alloy for best conductivity.

II. Theory

The two-pole filter schematic to be implemented is shown in Fig. 1(a). It consists of a second-order coupled resonator bandpass filter (with both capacitive and inductive couplings) in parallel with a feedback capacitor. The purpose of the feedback capacitor is to introduce a pair of finite transmission zeros to the transmission transfer function—one in the lower stopband and another one in the upper stopband. It will be demonstrated later that the passband characteristics of this filter and the

Manuscript received September 16, 2001; revised February 11, 2002. This work was supported by the Research Grants Council of the Hong Kong Special Administrative Region under Grant 2150237/4213/00E.

The authors are with the Department of Electronic Engineering, The Chinese University of Hong Kong, Shatin, Hong Kong (e-mail: klwu@ee.cuhk.edu.hk).

Digital Object Identifier 10.1109/TMTT.2002.807846

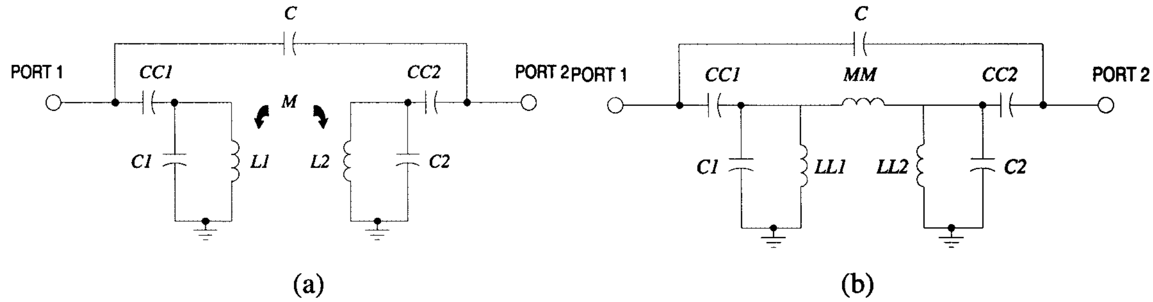


Fig. 1. (a) Schematic of the two-pole second-order filter. (b) Alternative representation of the filter schematic.

one without the feedback capacitor are almost the same. The overall admittance matrix for the filter schematic will be the sum of those for the coupled resonator filter and the feedback capacitor. In such a case, the overall admittance matrix is of the form

$$\mathbf{Y} = \begin{pmatrix} sC + y'_{11} & -sC + y'_{12} \\ -sC + y'_{21} & sC + y'_{22} \end{pmatrix} \tag{1}$$

where $s = j\omega$ and $y'_{11}, y'_{12}, y'_{21}$, and y'_{22} are the elements of the admittance matrix for the coupled resonator filter without the feedback capacitor. Using this admittance matrix, the location of the finite transmission zeros can then be obtained by solving the following equation:

$$-sC + y'_{12} = 0. \tag{2}$$

With this equation in mind, the next step is to obtain the expression for y'_{12}.

To simplify the analysis, the circuit in Fig. 1(a) is first transformed to the one shown in Fig. 1(b) using the Y-to-Delta transformation. The values of the inductors in this new configuration are given by

$$LL_1 = \frac{(L_1-M)(L_2-M)+(L_1-M)M+(L_2-M)M}{L_2-M} \tag{3a}$$

$$LL_2 = \frac{(L_1-M)(L_2-M)+(L_1-M)M+(L_2-M)M}{L_1-M} \tag{3b}$$

$$MM = \frac{(L_1-M)(L_2-M)+(L_1-M)M+(L_2-M)M}{M} \tag{3c}$$

and then, by performing the nodal analysis on the circuit of the coupled resonator filter, the element y'_{12} can be found as

$$y'_{12} = -\frac{sCC_1CC_2/MM}{\left(sC'_1 + 1/sL'_1\right)\left(sC'_2 + 1/sL'_2\right) - 1/s^2MM^2} \tag{4}$$

where

$$\left.\begin{aligned} C'_1 &= CC_1 + C_1 & C'_2 &= CC_2 + C_2 \\ L'_1 &= LL_1//MM & L'_2 &= LL_2//MM \end{aligned}\right\}. \tag{5}$$

Substituting (4) into (2) and rewriting it as

$$s^4C'_1C'_2 + s^2\left(\frac{C'_1}{L'_2} + \frac{C'_2}{L'_1} + \frac{CC_1 \cdot CC_2}{MM \cdot C}\right) + \left(\frac{1}{L'_1L'_2} - \frac{1}{MM^2}\right) = 0. \tag{6}$$

A fourth-order polynomial in s is obtained, and the locations of the two finite transmission zeros will then be the two positive roots of the polynomial. Alternatively, as shown in Section III, they can also be found by solving (2) and (4) graphically.

III. LTCC Filter Implementation

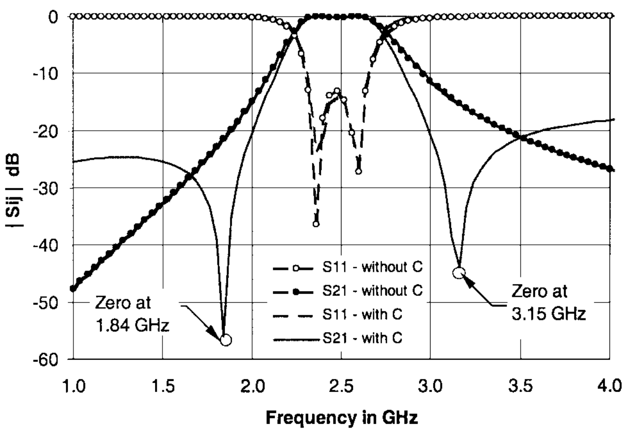
A. Circuit Model

Having discussed the theory in Section II, the filter realization and implementation issues will now be addressed in greater detail. The first step is to obtain the circuit model of the filter according to the desired specifications. Based on the synthesis method for a bandpass filter outlined in [8], a second-order Chebyshev-type bandpass filter of 0.2-dB ripple, 2.5-GHz center frequency, and 0.3-GHz equal-ripple bandwidth has been designed. The corresponding component values in Fig. 1(b) are $CC_1 = CC_2 = 0.79$ pF, $LL_1 = LL_2 = 1.55$ nH, $C_1 = C_2 = 2.48$ pF, and $MM = 9.27$ nH.

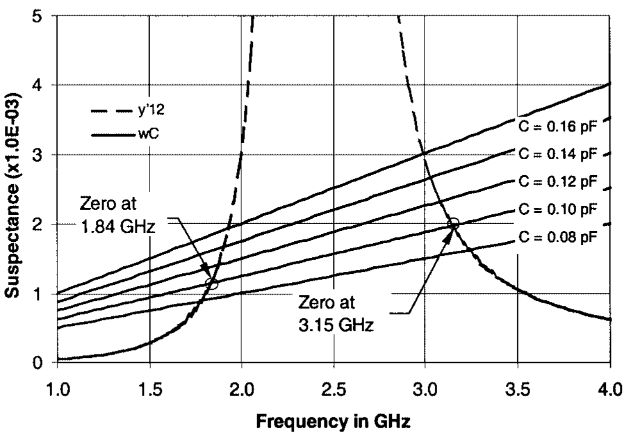
The dashed curves in Fig. 2(a) show the transmission and reflection responses of the Chebyshev filter. Notice that these responses are not symmetrical in shape. After obtaining the circuit model for the coupled resonator filter, the next step is to determine the value of the feedback capacitor. Depending on the desired locations of the transmission zeros, the value of the capacitor C can be selected to meet the requirement by a graphical method. As shown in Fig. 2(b), the locations of the zeros will simply be the intersections of the straight line of sC and the curve of y'_{12}. In this example, a 0.1-pF capacitor has been used and the corresponding zeros are locating at 1.84 and 3.15 GHz. With the insertion of this coupling capacitor, the responses of the filter are now changed to those shown in the solid curves of Fig. 2(a). It clearly shows that the two transmission zeros appearing at the stated frequencies and the passband characteristics are almost the same as the one without the capacitor C.

B. Physical Layout

While the two-pole filter was analyzed based on the circuit model of Fig. 1(b), the circuit model of Fig. 1(a) is a better choice for realization in LTCC. The reason is that the large-value inductor MM is replaced by a small-value mutual inductance M, which can easily be implemented by placing two inductors close to each other in vertical direction using LTCC technology, resulting in size reduction. In the experimental filter considered, the values of L_1, L_2, and M in Fig. 1(a) are 1.16, 1.16, and 0.19 nH, respectively.



(a)



(b)

Fig. 2. (a) Transmission and reflection responses of the filters. (b) Locations of the transmission zeros.

With the multilayer capability of the LTCC technology, the lumped-circuit model can be readily realized by using parallel plates for the capacitor and a metallic strip for the inductor. For the initial physical layout design, the simple, but well-known parallel-plate formula can be used to calculate the rough estimation on the dimensions of a capacitor. On the other hands, a more complicate formula is required for the estimation on an inductor or a mutual inductance between the two inductors. With the reference of Fig. 3, the formula for calculating the self-inductance of an infinite thickness strip or the mutual inductance between two such strips is given by [9]

$$\begin{aligned} M &= \frac{\mu}{4\pi} \\ &\cdot \frac{1}{ad}\Bigg[\Bigg[\frac{x^2-P^2}{2}\,z\ln\left(z+\sqrt{x^2+P^2+z^2}\right) \\ &\quad +\frac{z^2-P^2}{2}\,x\ln\left(x+\sqrt{x^2+P^2+z^2}\right) \\ &\quad -\frac{1}{6}\,(x^2-2P^2+z^2)\sqrt{x^2+P^2+z^2} \\ &\quad -xPz\tan^{-1}\frac{xz}{P\sqrt{x^2+P^2+z^2}}\Bigg]_{E+d-a,\,E}^{E-a,\,E+d}(x)\Bigg]_{l_3+l_2-l_1,\,l_3}^{l_3-l_1,\,l_3+l_2}(z). \end{aligned} \tag{7}$$

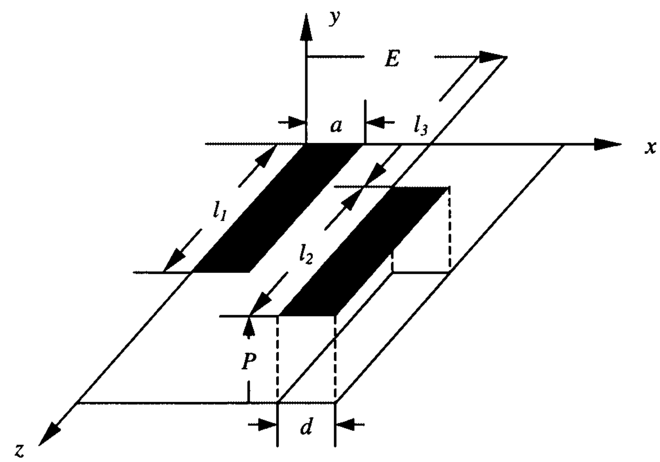


Fig. 3. Geometry for two parallel strips.

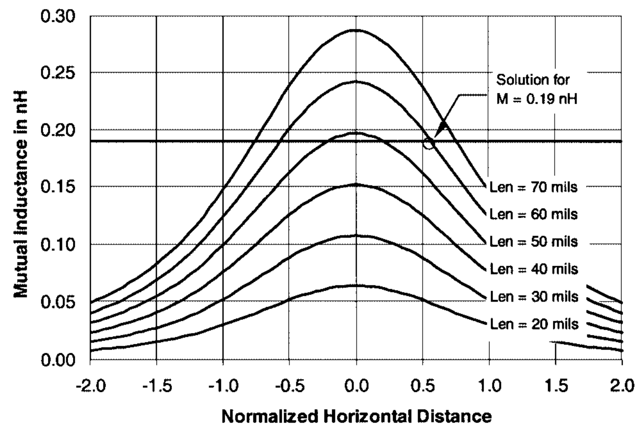


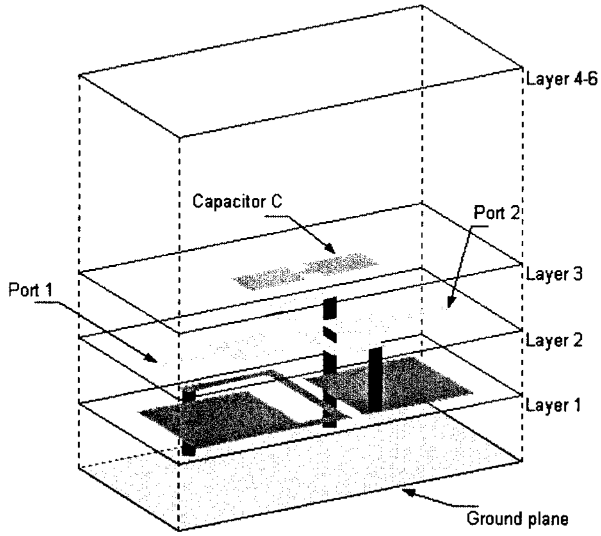
Fig. 4. Mutual inductance versus separation distance (ground plane at $z = 0$ mil, two strips with $a = d = 8$ mil, and $P = 3.6$ mil).

In Fig. 4, the mutual inductance of two 8-mil-width strips (for different strip length *Len*) as a function of normalized horizontal separation distance is shown. Notice that the strips are locating at two different layers (separated by an LTCC substrate of 3.6 mil in thickness). It can be seen from this figure that a mutual inductance of 0.19 nH can be achieved by combining different strip lengths and separation distances. In the experimental filter, two 8 $\times$ 60 mil^2 strips separated by a distance of $0.57 \times 8 = 4.56$ mil were used.

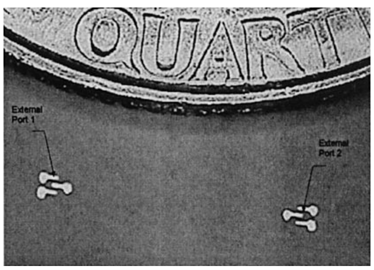
Having had these formulas, the initial physical layout of the proposed filter can then be easily set up. A fine tuning is required to accommodate the parasitic effects of each lumped element, mutual coupling effects between elements, and finalize the layout design by employing full-wave electromagnetic (EM) simulation tools, e.g., IE3D, Zeland Software, Fremont, CA, in this study.

IV. Experimental Results

An experimental filter has been designed and built in an LTCC format at the LTCC Division, National Semiconductor Corporation, Santa Clara, CA, according to the procedures outlined above. Fig. 5 shows the physical layout of the filter. It was constructed inside an LTCC substrate (Dupont 951AT) of six layers with 3.6-mil thickness. The components of the filter



(a)



(b)

Fig. 5. (a) Physical LTCC layout of the filter. (b) Experimental prototype.

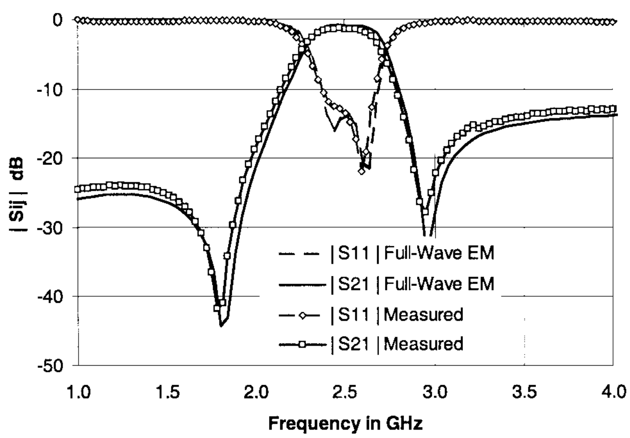


Fig. 6. Comparison of the full-wave EM simulation and the measurements of a prototyped LTCC filter of the proposed configuration.

were located only at the interfaces between the bottom four layers. The overall size of the filter is $170 \times 80 \times 21.6$ mil^3.

A few points about the filter are worth mentioning. Firstly, a finite ground plane was inserted at the bottom of the substrate for the construction of the grounded resonators. Secondly, the feedback coupling capacitor was implemented by placing a "dumbbell"-shaped metal plate directly above the input and output components of the filter. Finally, the mutual inductance in the filter design was realized by overlaying two inductance strips one above the other.

The measurement was carrying out by connecting a probe station to the two external ports [shown in Fig. 5(b)] of the device. The collected data was then calibrated to the desired reference plane by the thru-reflect line (TRL) technique through carefully designed calibration standards embedded in the same LTCC tile. The measured responses of the filter together with those from EM simulation are presented in Fig. 6. It can be seen that, due to the zero metallic strip thickness model used in the design, which underestimates the capacitance of the parallel plates, the measured responses are slightly shifted toward the lower frequency end. Nevertheless, the correlation of the theoretical and measured results is very good. Notice that the two finite zeros in the transmission response of the filter are located at the prescribed locations.

V. Conclusions

In this paper, a compact LTCC second-order filter has been presented. It has utilized a simple feedback coupling capacitor between the input and output ports to produce two finite transmission zeros in the transfer function. It has been demonstrated that the filter not only has a better selectivity, but also has nearly the same passband characteristics as those of the traditional second-order coupled-resonator filter. The mathematical formula and graphical design procedure for the well-known two-pole filter schematic have been provided with detailed derivation. Practical LTCC implementation issues have also been discussed. Very good agreement can be observed between the designed responses and experimental results.

Acknowledgment

The authors are very grateful to the LTCC Division, National Semiconductor Corporation, Santa Clara, CA, for providing LTCC prototyping support. Many thanks are also extended to Dr. M. Ehlert. National Semiconductor Corporation, and Dr. W. R. Smith, Ditrans Corporation, Irvine, CA, for helpful discussions.

References

[1] J. W. Sheen, "A compact semi-lumped low-pass filter for harmonics and spurious suppression," *IEEE Microwave Guided Wave Lett.*, vol. 10, pp. 92–93, Mar. 2000.
[2] J. W. Sheen, "LTCC-MLC duplexer for DCS-1800," *IEEE Trans Microwave Theory Tech*, vol. 47, pp. 1883–1890, Sept. 1999.
[3] T. Ishizaki, H. Miyake, T. Yamada, H. Kagata, H. Kushitani, and K. Ogawa, "A first practical model of very small and low insertion loss laminated duplexer using LTCC suitable for W-CDMA portable telephones," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 2000, pp. 187–190.
[4] "World's smallest GSM front-end module in LTCC technology," EPCOS, Munich, Germany, News Release, July 2001.
[5] A. Sutono, J. Laskar, and W. R. Smith, "Development of three dimensional integrated Bluetooth image reject filter," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 1, Boston, MA, 2000, pp. 339–342.
[6] K. Noboru *et al.*, "Composite electronic component and frequency adjustment method of the same," U.S. Patent 5 140 497, 1992.
[7] I. Awai, A. C. Kundu, and T. Yamashita, "Equivalent-circuit representation and explanation of attenuation poles of a dual-mode dielectric-resonator bandpass filter," *IEEE Trans Microwave Theory Tech*, vol. 46, pp. 2159–2163, Dec. 1998.
[8] G. L. Matthaei, L. Young, and E. M. T. Jones, *Microwave Filters Impedance Matching Networks and Coupling Structures*. New York: McGraw-Hill, 1980, pp. 355–410.

[9] C. Hoer and C. Love, "Exact inductance equations for rectangular conductors with applications to more complicated geometries," *J. Res. Natl. Bur. Stand.*, vol. 69C, no. 2, pp. 127–133, 1965.

Lap Kun Yeung (S'00) received the B.Eng. degree in electrical and information engineering from the University of Sydney, Sydney, Australia, in 1998, and is currently working toward the M.Eng. degree with the Chinese University of Hong Kong, Shatin, Hong Kong.

During 1999, he was with the Commonwealth Scientific and Industrial Research Organization (CSIRO), Melbourne, Australia, where he was a Research Engineer involved in the numerical modeling of different antenna structures. He is currently with the Chinese University of Hong Kong, where he is involved with the development of numerical algorithms for analyzing multilayer embedded RF circuit modules.

Ke-Li Wu (M'90–SM'96) received the B.S. and M.Eng. degrees from Nanjing University of Science and Technology, Nanjing, China, in 1982 and 1985, respectively, and the Ph.D. degree from Laval University, Quebec, QC, Canada, in 1989.

From 1989 to 1993, he was with the Communications Research Laboratory, McMaster University, Montreal, QC, Canada, as a Research Engineer and a Research Group Manager. In March 1993, he joined the Corporate Research and Development Division, Com Dev International, where he had been a Principle Member of Technical Staff in charge of developing advanced EM design software for various microwave subsystems for communication satellites and wireless communications. Since October 1999, he has been with the Department of Electronic Engineering, The Chinese University of Hong Kong, Hong Kong, where he is a Professor. He has authored or coauthored numerous publications in the areas of EM modeling and microwave and antenna engineering. He holds one Canadian patent and one U.S. patent. He contributed to *Finite Element and Finite Difference Methods in Electromagnetics Scattering* (Amsterdam, The Netherlands: Elsevier, 1990) and *Computational Electromagnetics* (Amsterdam, The Netherlands: Elsevier, 1991). His current research interests include all the aspects of numerical methods in electromagnetics, various passive microwave circuits, integrated antenna arrays, and LTCC multichip modules (MCMs) for wireless communications.

Dr. Wu was the recipient of a 1992 URSI Young Scientist Award. He was also the recipient of the 1993 Industry Feedback Award from the Telecommunication Research Institute of Ontario, Canada, and the 1998 Com Dev Achievement Award.