A Compact LTCC Bluetooth System Module with an Integrated Antenna

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ABSTRACT: In this article, a system-on-package (SoP) approach for Bluetooth system module applications using low-temperature co-fired ceramic (LTCC) technology is presented. The developed LTCC integrated substrate for our Bluetooth module application is overall 12 × 12 × 1 mm^3 in size, with integration of two originally proposed components, a balanced-to-unbalanced bandpass filter and a folded meander-line inverted-F antenna, as well as other passive circuitries. The embedded balanced-to-unbalanced filter, which is derived from the basic center-tapped transformer circuit, works simultaneously as a balun and a bandpass filter, thus leading to a significant amount of size reduction for the overall module. Likewise, comparing to the usual quarter-wavelength inverted-F antennas, our proposed antenna is only one-tenth of a wavelength in length—but no sacrificing of antenna efficiency. Consequently, couplings among different functional blocks of this highly integrated module are crucial to its performance and the resulting effects are discussed. A fully functional prototype is successfully fabricated and tested, demonstrating a promising solution for Bluetooth applications. Int J RF and Microwave CAE 16: 238–244, 2006.

Keywords: antenna; balun; Bluetooth; filter; LTCC; system-on-package

I. INTRODUCTION

There is an ever-increasing demand for fast and reliable ad-hoc wireless data transfer between two or more consumer electronic devices. Typical applications include mobile phones, PDAs, portable computers, cameras, and printers. Currently, a common solution for such demand is the Bluetooth protocol for ad-hoc networks operating at 2.45 GHz. Under this scenario, each member in the network, namely, a consumer electronic device, should be equipped with a Bluetooth module [1] in order to enable standardized data transfer. Undoubtedly, this Bluetooth-based communication capability will be playing an important role in current and future consumer electronics. For an attractive implementation of such modules, cost and compactness are the two most fundamental concerns.

Low-temperature co-fired ceramic (LTCC) technology, due to its attributes of low volume production cost, multilayered 3D configuration, and low RF loss, has been widely used in various integrated microwave/RF front-end modules and discrete RF functional components. For various applications, a multilayered LTCC SoP implementation with integrated passive functional components, which otherwise have to be acquired in discrete form as part of the package substrate, would be a very desirable goal. Furthermore, the use of on-package components can eliminate the need for discrete components and therefore reduce the cost. Various LTCC-based front-end modules have been reported recently [2–4]. Some LTCC-

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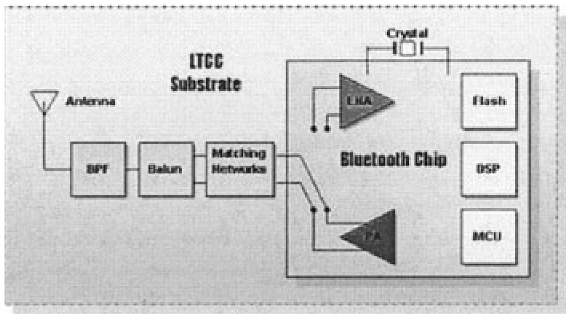

Figure 1. System block diagram for the proposed Bluetooth system module.

based Bluetooth modules are also available on the market [1]. However, all the available Bluetooth modules have unfavorable sizes or are oversized (if antenna is integrated).

This article presents a newly developed Bluetooth module substrate which is only $12 \times 12 \times 1$ mm^3 in size. Moreover, two originally proposed components, a balanced-to-unbalanced filter [5] and a folded meander-line inverted-F antenna [6] are also presented in the context of system integration. A significant amount of size reduction is achieved for each of these components by combining two functional elements into one in the first device and utilizing a 3D spiral structure in the second device.

II. SYSTEM COMPONENTS

Figure 1 shows a simplified system block diagram of our LTCC Bluetooth module. Notice that three main embedded functional components are the antenna, the bandpass filter, and the balun. At the same time, a Bluetooth chip, a crystal and a number of discrete components (not shown) are mounted on top of the LTCC substrate. During transmitting mode of operation, the balun and bandpass filter complex converts a balanced signal from the power amplifier to an unbalanced signal for transmission through the antenna. In contrast, the opposite is true during the receiving mode of operation. This particular complex should also have a well-defined filtering function such that unwanted out-of-band signals will be rejected. In addition, matching networks are required between the balun and power-amplifier transition to ensure an optimal matching condition.

A. Balanced-to-Unbalanced Filter

The balun and bandpass filter complex shown in Figure 1 can be realized in an obvious way by using two separate components — a balun and a bandpass filter. However, this method usually requires a larger space for realization, since there are two components to be implemented. On the other hand, if it is realized as one single functional device (as in this case), a new aspect for size reduction is created. This functional component is referred as a balanced-to-unbalanced filter or balun-filter. Besides its balun-type operation, the balun-filter used in our module is designed to have 3rd-order bandpass filtering characteristics. Moreover, a strong rejection is introduced at 1.9 GHz by means of an extracted-pole technique. Figures 2 and 3 show its physical layout and measured *S*-parameter, respectively. Note that it resembles a 3rd-order coupled-resonator filter and a center-tapped transformer circuit is used to carry out the balun-type operation. The center-tapped transformer is realized by two closely-spaced conductor strips and their separation distance is used to control the mutual inductance between them. Due to the 3D integration flexibility of LTCC technology, ten conductor layers are used to implement this device, with ground planes printed on the first and last layers for shielding purpose. The initial layout dimensions are obtained by using our in-house dynamic-design software, which is based on a quasi-static EM modeling algorithm. A space-mapping optimization technique is then used to fine-tune these layout dimensions. In a space-mapping optimization, the results from each full-wave simulation are compared with desired 'golden template' responses, and a quasi-static EM model is used to extract necessary dimension adjustments at each iteration step. This process continues until a close match is obtained.

For the measured results, an insertion loss of 2.6 dB, an amplitude balance within 0.5 dB, and a phase different within $180° \pm 1°$ are achieved. Also note that a sharp rejection appears around 1.9 GHz at each transmission response (S_{12} and S_{13}), as expected. It is found that the return loss (S_{11}) of this device, or any 3rd-order coupled-resonator in general, is more sensitive to the second resonator than the other resonators. Hence, special attention is required when implementing those second-resonator components.

B. Antenna

The antenna is another essential functional component in the system module. As seen in Figure 4, our proposed antenna is an inverted-F antenna (IFA) in principle with a folded meander line as a radiating arm. With this meandering radiator structure, the length of the proposed antenna is reduced significantly whereas it possesses a sufficient value of radiation impedance. It can be initially designed by setting the 'stretched' radiating arm length to be a quarter-wavelength long.

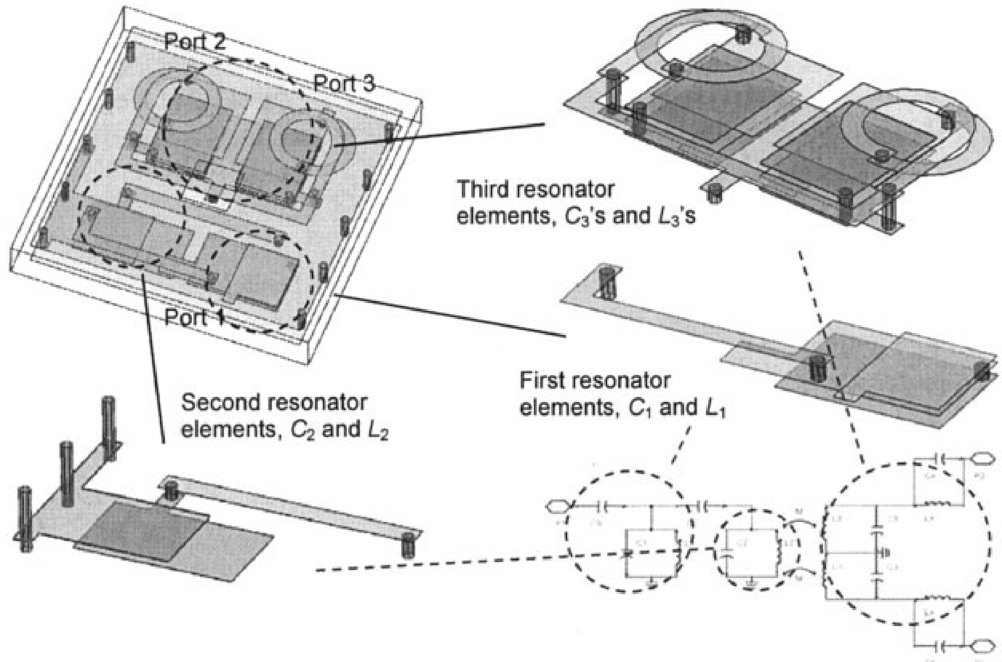

Figure 2. Physical layout of the proposed balun-filter.

This 'stretched' length includes all the lengths of printed conductor traces and via holes. The final geometry dimensions must be obtained through a full-wave electromagnetic solver in order to achieve a good match to 50Ω source impedance.

However, in different applications of the module, influences from the surrounding environment to the antenna resonant frequency are different. To accommodate any detuning of the antenna, a conventional L-type matching network with a series inductor and a shunt capacitor is used to tune the frequency back down to 2.45 GHz. Figure 5 shows various measured return losses under different capacitance values and an inductance value of 0.8 nH. Under any condition, the antenna bandwidth of −10-dB return loss is more than 100 MHz. In addition, the measured peak gain of this antenna is better than 1.5 dBi, which is comparable to the standard meander-line or helix chip antenna that is mounted perpendicularly to the ground edge.

III. ELECTROMAGNETIC COMPATIBILITY IN SYSTEM DESIGN

In designing a compact RF system module which comprises various functional circuitries, EM interfer-

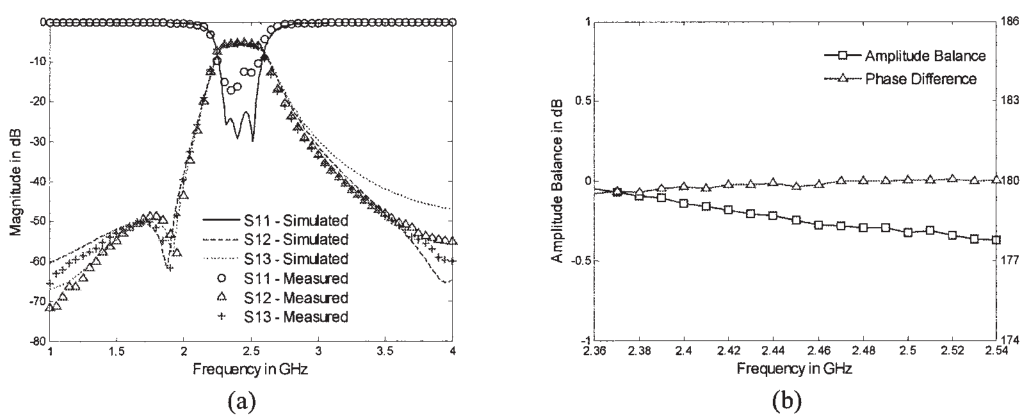

Figure 3. Measured (a) *S*-parameter and (b) amplitude balance and phase difference of the balun-filter.

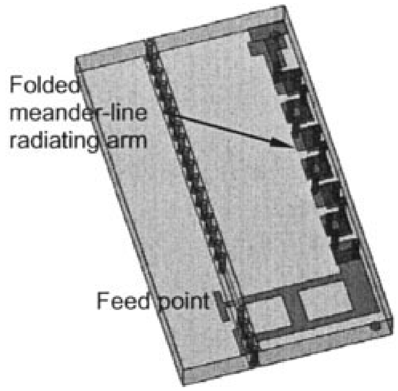

Figure 4. Physical layout of the proposed antenna.

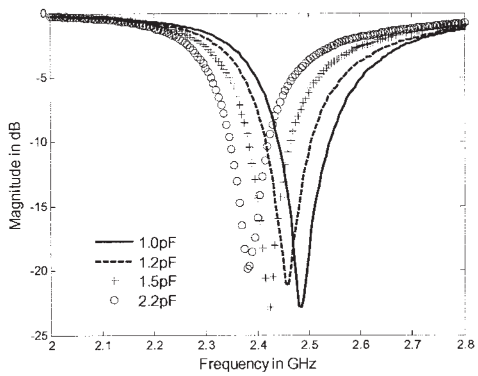

Figure 5. Antenna return losses with different matching capacitors.

ence among these circuitries is always a thorny issue. It is important to diagnose and minimize the hostile but parasitic couplings, since they can drastically degrade the module's performance or, in the worst case, prevent it to function properly. One major concern in compact-module design is to minimize the amount of transmitted RF energy re-entering the module. A high-level RF coupling can interfere with the VCO and corrupt the crystal frequency reference. Figures 6(a) and 6(b) respectively show the transmitter output spectra, one with a high level of RF coupling and the other with a normal level of RF coupling. The underlying principle in these measurements is that when RF coupling is present, transmitting an offset carrier of frequency (f_0 + offset) will effectively modulate the VCO output by a sinusoid wave of a frequency that is the same as the offset. This modulation will appear at the transmitter output and the heights of these sidebands can be used to justify the degree of RF coupling within the particular module of interest. High-level RF coupling, such as the one shown in Figure 6(a), degrades the module's performance significantly. Another major concern is to prevent the transmitted RF energy contaminating the power supply. In our application, power is provided to the power amplifier through the balun-filter, and this means that the power tracks are in direct contact with the RF circuitries. If there is no sufficient filtering, the supply voltage may become unstable which, in turn, prevents other functional components from operating properly. As an

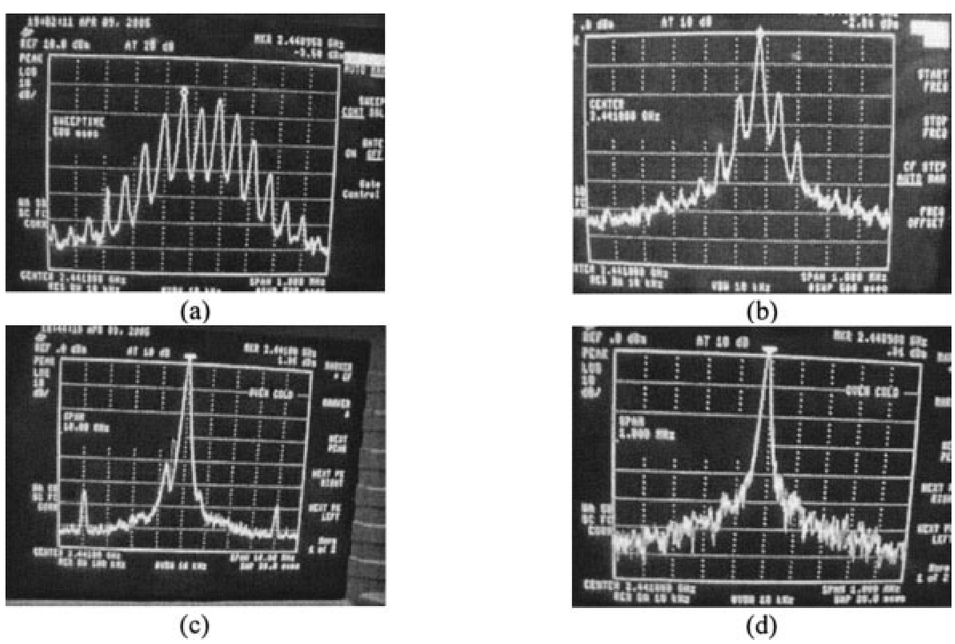

Figure 6. Transmitter output spectra under (a) a high-level RF coupling, (b) a normal-level RF coupling, (c) a contaminated power supply, and (d) a stable power supply.

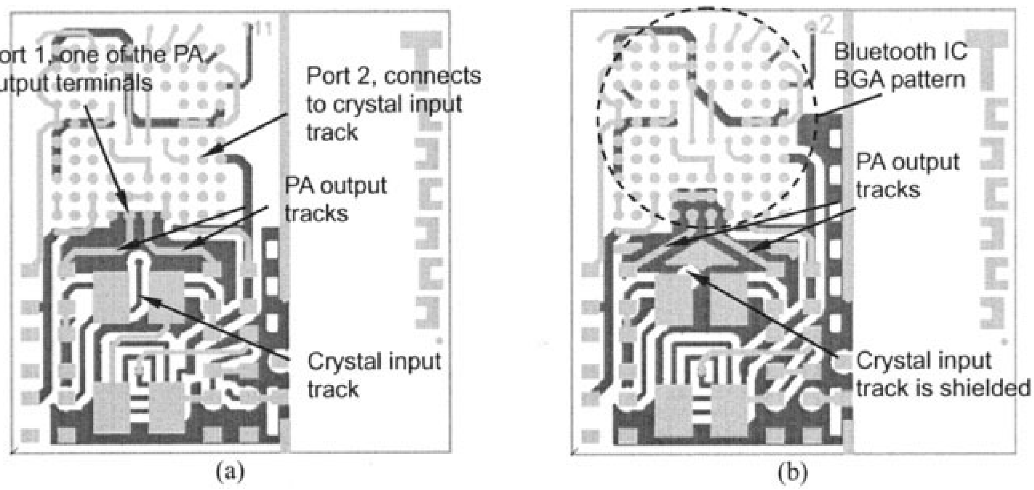

Figure 7. Conductor layout of the top two layers from two different module layouts: (a) case 1; (b) case 2. Top-layer printings are in light grey, whereas second layer printings are in dark grey.

example, Figure 6(c) shows a pure carrier spectrum of a module with contaminated power supply. In this case, a 4.7-pF decoupling capacitor located close to the balun-filter is used. It is seen that there are unwanted tones in the spectrum besides the carrier. On the other hand, when a 100-nF decoupling capacitor is used, a "clean" carrier spectrum is obtained [Fig. 6(d)].

Inappropriate placement of crystal tracks can also corrupt the crystal frequency reference and which, in turn, causes instability in the VCO output frequency. Figure 7 shows two simplified example layouts that have different levels of RF back coupling to the crystal input track. The crystal input track in case 1 is not as well shielded from the power amplifier outputs as that of case 2. This leads to a higher level of RF coupling to the track in case 1 (Fig. 8), and thereby a higher VCO drift-rate and a worse overall performance, and consequently, occasional communication link drop-out.

Another important issue in designing a module is its grounding mechanism, especially for a compact one. Ideally, conductor ground printings should be filled in every layer and occupy as much empty area as possible. Moreover, these ground printings should be well connected to each other. Unfortunately, due to a possible bowering problem of the LTCC substrate, the conductor layout on each layer is usually kept less than 50% of area of each single layer. Therefore, a judicious routing scheme which minimizes the mode disturbances and mode couplings should be adopted.

Taking all the issues into consideration, a fully functional Bluetooth module prototype has been built and tested. This module has a maximum communication distance of more than 17 m and a sensitivity of approximately −75 dB. Further improvements of RF

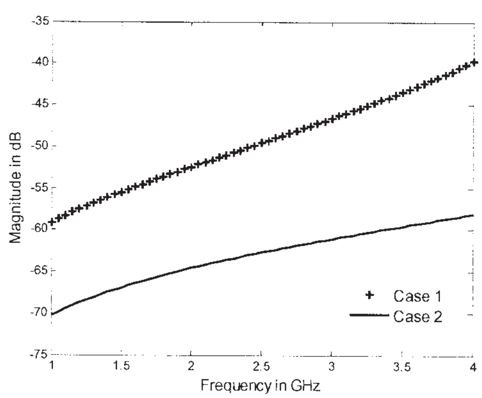

Figure 8. The simulated couplings between port 1 and port 2 in the two models shown in Fig. 7.

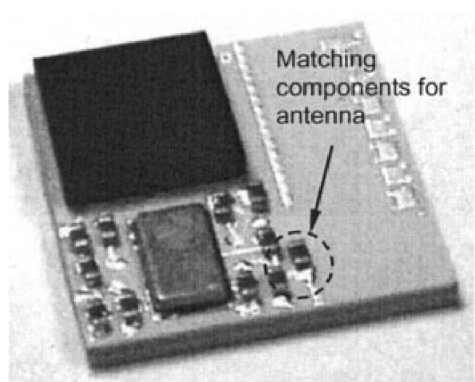

Figure 9. The prototype LTCC Bluetooth module with surface-mounted components.

coupling isolation, EM interference minimization, and size reduction of the module are underway.

IV. CONCLUSION

A compact LTCC SoP front-end module for Bluetooth application has been designed, fabricated, and tested. Two critical embedded components, namely, a balun-filter and an antenna, have been successfully developed, characterized, and integrated into the module so that significant size reduction is obtained. Furthermore, it has been determined that at such a high-level of integration, parasitic couplings will significantly degrade the module performance if they are not carefully controlled. Through its continuing improvement and size reduction, the compact and fully functional prototype shows the promising potential of LTCC technology for future wireless consumer electronics.

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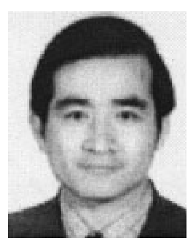
REFERENCES

1. R. Kulke, V. Wahle, D. Sollbach, P. Uhlig, M. Rittweger, S. Schmitz, and P. Waldow, High level of integration for Bluetooth modules on LTCC, 14th Euro Micro Packaging Conf, Friedrichshafen, Germany, 2003.
2. Y. Ko, J. Park, J. Ryu, K. Lee, and J. Bu, A miniaturized LTCC multilayered front-end module for dual-band WLAN (802.11a/b/g) applications, IEEE MTT-S Int Microwave Symp Dig 2 (2004), pp. 563–566.
3. C. Lee, A. Sutono, C. Lee, S. Han, K. Lim, S. Pinel, E. Tentzeris, and J. Laskar, A compact LTCC-based Ku-band transmitter module, IEEE Trans Adv Packaging 25 (2002), 374–384.
4. S. Chakraborty, K. Lim, A. Sutono, E. Chen, S. Yoo, A. Obatoyinbo, and J. Laskar, Development of an integrated Bluetooth RF transceiver module using multilayer system on package technology, IEEE Radio Wireless Conf, Boston, MA, 2001.
5. L. Yeung and K. Wu, An integrated RF balanced-filter with enhanced rejection characteristics, IEEE MTT-S Int Microwave Symp Dig 2 (2005).
6. K.-L. Wu, Y. Huang, and W.-C. Tang, A folded meander-line inverted-F antenna for compact RF module applications, IEEE Microwave Wireless Compon Lett (submitted).

BIOGRAPHIES

Lap K. Yeung received his B.Eng. degree in electrical and information engineering from the University of Sydney, Sydney, Australia, in 1998, and his M.Eng. degree in electronic engineering from the Chinese University of Hong Kong, Shatin, Hong Kong, in 2002. During 1999, he was with the Commonwealth Scientific and Industrial Research Organization (CSIRO), Sydney, Australia, where he was a Research Engineer involved in numerical modeling of time-domain scattering problems. He is currently with the Chinese University of Hong Kong, where he is involved in the development of numerical algorithms for analyzing and designing multilayer embedded RF circuit modules.



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Ke-Li Wu received B.S. and M.Eng. degrees from Nanjing University of Science and Technology, Nanjing, China in 1982 and 1985, respectively, and his Ph.D. degree from Laval University, Quebec, QC, Canada in 1989. From 1989 to 1993, he was with the Communications Research Laboratory, McMaster University, Hamilton, ON, Canada. In March 1993, he joined the Corporate Research and Development Division, Com Dev International, as a Principal Member of Technical Staff in charge of developing advanced EM design software for various microwave subsystems. Since October 1999, he has been with the Department of Electronic Engineering, The Chinese University of Hong Kong, Shatin, Hong Kong, where he is a Professor. He has authored or co-authored numerous publications in the areas of electromagnetic (EM) modeling and microwave and antenna engineering. He contributed to "Finite Element and Finite Difference Methods in Electromagnetics Scattering" (Elsevier, 1990) and "Computational Electromagnetics" (Elsevier, 1991). He holds two patents. His current research interests include all the aspects related to low-temperature co-fired ceramic (LTCC) multichip modules (MCMs) from EM modeling to design methodology and various applications. He was a recipient of the 1992 URSI Young Scientist Award and the 1998 Com Dev Achievement Award.