LINE-LOSS AND SIZE-REDUCTION TECHNIQUES FOR MILLIMETER-WAVE RF FRONT-END BOARDS BY USING A POLYIMIDE/ALUMINA-CERAMIC MULTILAYER CONFIGURATION

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ABSTRACT

This paper proposes a concept for constructing low-loss and small-size millimeter-wave RF front-end boards by using a polyimide/alumina-ceramic multilayer configuration. This configuration enables us to design wide line-width low-loss microstrip lines. In addition, the board size can be reduced by compactly arranging all RF and DC lines in the intermediate layers of the polyimide/alumina-ceramic substrate. A prototype board designed for the quasi-millimeter-wave region was successfully demonstrated with good performance.

INTRODUCTION

Millimeter-wave frequencies are an attractive and abundant spectrum resource for high-speed radio communication systems. Millimeter-wave RF technologies still need further cultivation, however, before application to practical consumer products. For cordless and cellular terminals, the use of multilayer glass epoxy boards is a good solution for reducing their size and fabrication cost. However, their application to millimeter-wave substrates incurs difficulties because of the line-loss which increases in proportion to the frequency. Consequently, to build high-performance mobile terminals, line-loss and size-reduction techniques suitable for millimeter-wave RF module boards are required.

For large scale integration and chip-size reduction, 3-D MMICs have been proposed [1]. They adopt multilayer polyimide to form Thin Film MicroStrip lines (TFMSs). Their flexibility of patterning on the semiconductor chip allows us to connect many functional unit circuits within a small area and fabricate multi-functional one-chip MMICs [2]. Since each unit circuit shares the same semiconductor substrate, it is hard to integrate circuits fabricated by different device-processes into one circuit-module. The ability to join different types of active devices improves the total circuit performance and increases the field of 3-D MMIC technology applications.

We propose a concept for reducing line-loss and module-size by using a polyimide/alumina-ceramic multilayer configuration. In this configuration, the wide line-width transmission lines and passive RF circuits can be neatly patterned in the multilayered polyimide. DC-bias lines can be compactly arranged in the intermediate layer of the multilayered ceramic substrate. All MMICs, voltage regulators, inverters and controller ICs can be mounted on the substrate. This configuration is successfully applied to the RF module board for the quasi-millimeter-wave region.

PROPERTIES OF POLYIMIDE/ALUMINA-CERAMIC

Glass epoxy and alumina ceramic are often used for the substrates of the RF circuits. We compared the properties of polyimide/alumina-ceramic with those of glass epoxy and alumina ceramic. The results are summarized in Table 1.

Table 1 Comparison of multilayer substrate materials

	PI/ceramic	Alumina	Glass Epoxy
Cost	○	○	◎
RF performance (>10 GHz)	○	◎	×
Size	◎	△	○
Fine pattern	○	△	○
Easy fabrication	△	△	◎

◎ : Excellent ○ : Good △ : Fair × : Poor

Glass epoxy is superior to other materials in terms of cost and ease of fabrication. This is the reason that glass epoxy substrate is now widely adopted for many kinds of RF boards. However, its RF performance degrades with an increase in

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frequency because of its large loss tangent. Therefore, it is difficult to apply this substrate to RF boards for the millimeter-wave range.

When the transmission lines are formed on the alumina surface, they show excellent performance even in the millimeter-wave region thanks to the small loss tangent. Despite this performance, they have drawbacks in size reduction and fine patterning. Multilayer alumina substrates are usually produced by a co-fired process. Because lines inside the ceramic substrate are patterned with screen printing techniques, their resolution is coarser than that of photolithography. Moreover, these lines need to be made from high-melting-point metals. Since they have higher sheet resistance than the conductors plated on the surface, only the lines on the surface of the substrate are available for the low-loss RF lines. This causes limitations in pattern layout.

Polyimide/alumina-ceramic inherits advantages from alumina, and can effectively combine these with the advantages of a multilayer polyimide structure. Since all transmission lines in multilayer polyimide can be fabricated by photolithography, low line-loss and fine patterning become possible. The loss of the wide MicroStrip lines (MSs) in this structure is measured and compared with those of CPWs on GaAs substrate and TFMSs (Fig. 1). The losses at 20 GHz for wide MSs, TFMSs and CPWs are 0.083 dB/mm, 0.34 dB/mm and 0.22 dB/mm, respectively. The wide MSs have approximately 1/4 the loss of the TFMSs, and this result shows their suitability for RF lines and passive circuits. Furthermore, lines inside the ceramic substrate can be adopted as DC-bias lines for the MMIC chips, which contributes to reducing the board size.

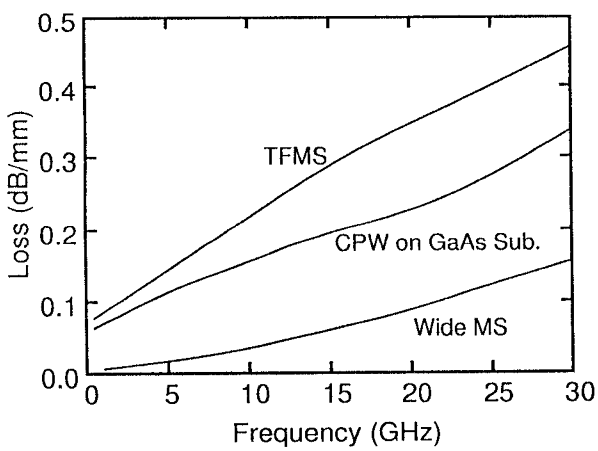


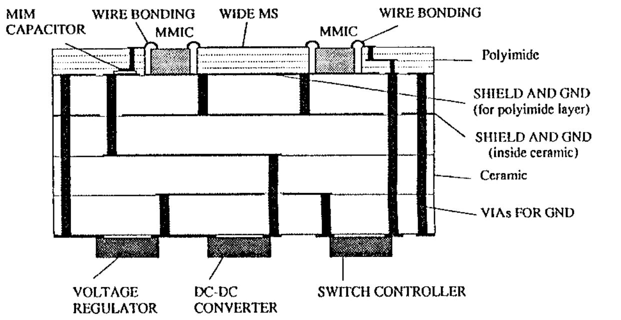
Fig. 1 Loss comparison

For these reasons, we propose to employ polyimide/alumina-ceramic as the substrate for the millimeter-wave RF front-end boards.

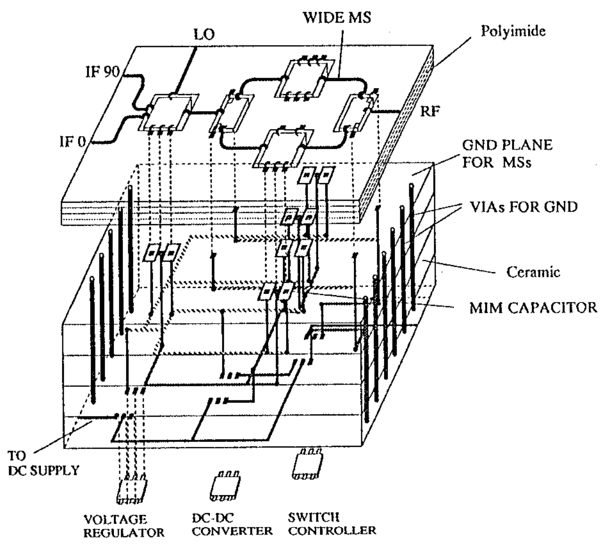
CONFIGURATION

The methods considered, for acheiving low-loss and small-size boards with a polyimide/alumina-ceramic multilayer configuration, are 1) line loss reduction by using wide MSs, 2) size reduction by mounting all ICs on the surface of the substrate and by arranging all lines three-dimensionally, and 3) circuit stabilization by using MIM capacitors fabricated on the ceramic substrate.

The proposed configuration is shown in Fig. 2. The board consists of four 25-μm-thick polyimide layers and four 250-μm-thick ceramic layers. The metal used in the polyimide layer is copper, and in the ceramic layer is tungsten. Between polyimide and ceramic layers, a ground plane is inserted to form



(a) Cross section



(b) Overview

Fig. 2 Schematics of the proposed configuration the ground for RF lines and to avoid interference between RF and DC-bias lines. Owing to this ground plane, the transmission lines for RF signals and DC-bias lines can be designed separately. MIM capacitors are also fabricated on this surface.

The polyimide layer is thick enough to allow the design of wider MSs than TFMSs. The wide MSs are used as the RF signal lines for MMICs. The multilayer ceramic substrate holds the MMICs on the polyimide-side surface, while on the ceramic-side are other ICs for the DC biases, such as voltage regulators, DC-DC converters, RF-switch controllers, etc. Rectangular areas of the polyimide layer were removed to open the mounting areas for MMICs. The MMICs were then glued on the ceramic surface with conductive paste. The DC-bias lines were formed on the ceramic surface or inside the ceramic substrate. One end of each DC-bias line was connected to the ICs for the DC biases at the ceramic surface. The other end was drawn to the top polyimide surface through a via-hole to be connected to the bias/control pads of the MMICs. In order to stabilize circuit operation and to eliminate parasitic oscillation, MIM capacitors were formed on the alumina substrate surface [3], and they were connected to the DC-bias lines as by-pass capacitors. All lines were bonded to the MMICs with 20-μm gold wires. RF lines were especially tightly connected with some minimal-length wires.

Amplifiers, RF switches and a mixer were mounted on the substrate. The TX branch is composed of four GaAs MESFET MMIC chips. The RX branch is composed of a PHEMT chip and a GaAs MESFET MMIC chip. The mixer is a subharmonically pumped one using anti-parallel diodes [4,5]. This mixer can be used for an up and down converter.

RESULTS AND DISCUSSIONS

Figure 3 shows the photographs of the prototype RF board, seen from the RF circuit surface (polyimide surface) and the DC-bias IC surface (ceramic surface). Nine MMIC chips are mounted on the polyimide surface. On the ceramic surface, five DC-bias ICs, some chip-resisters and chip-capacitors are soldered. The area occupied by these chips is 30 mm by 30 mm, excluding the DC connector area. The size of this module can be reduced to 25 mm by 25 mm by cutting off the design margin space.

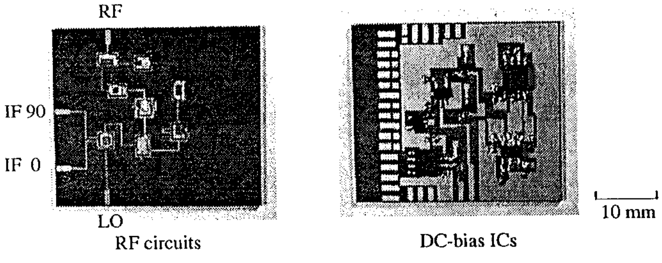


Fig. 3 Photographs of the prototype board

The performance of the board was measured in TX and RX modes. The injected LO power was 9 dBm and its frequency was 9.6925 GHz, which was subharmonically doubled and mixed in the mixer. IF was chosen as 140 MHz. The performance of the board in TX mode is shown in Fig. 4. It shows 23.2 dB gain, and 7.4 dBm P_{-1} output power. The performance of the board in RX mode is shown in Fig. 5. It shows 3.1 dB gain, and -20.1 dBm P_{-1} output power. When these performance measurements were made, there was no parasitic oscillation.

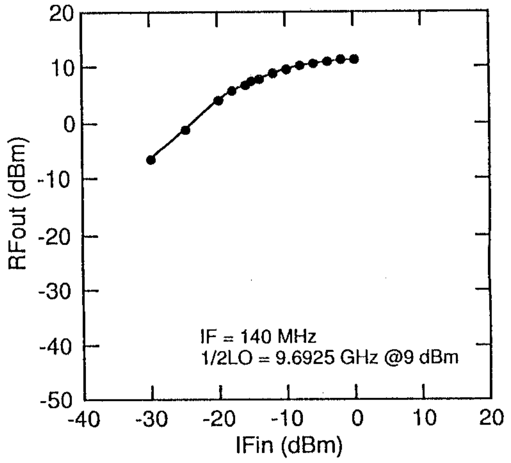


Fig. 4 Performance of the board: TX mode

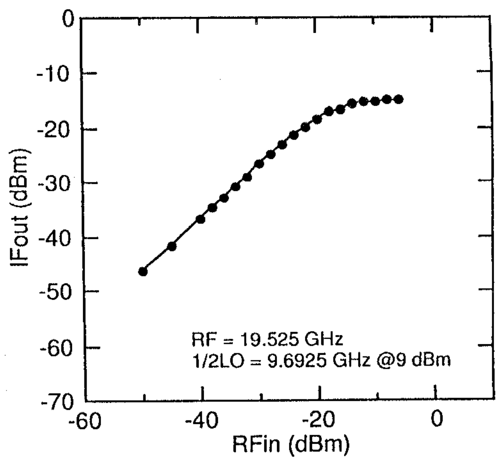


Fig. 5 Performance of the board: RX mode

Comparing to the predicted performance from TEG measurements, the performance levels obtained through experiments with this board are reasonable. The transmission loss is sufficiently low, and all MMICs and DC-bias ICs operate without difficulties. These experimental results confirm the validity of the proposed configuration, which is applicable to millimeter-wave RF module boards.

In the prototype board, the polyimide layer is used only for connecting MMIC chips. The multilayer polyimide structure has advantages in the fabrication of some kinds of passive circuits, such as broadside couplers [6], filters [7] and power dividers/combiners [1]. The proposed configuration has enough potential to integrate these passive circuits with MMIC chips and can improve the total performance in terms of the RF characteristics, board size and fabrication cost.

CONCLUSION

A multilayer polyimide/alumina-ceramic substrate was successfully applied to quasi-millimeter-wave band modules. The low-loss performance of the wide MSs exhibits their suitability for use even in the millimeter-wave region. The three-dimensional line layout contributes to module size reduction. These results are promising for realizing millimeter-wave module boards. These modules are suitable for application as RF boards of millimeter-wave mobile terminals.

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