MEMS-based transmission lines for microwave applications

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ABSTRACT
This paper mainly presents a brief review for recent progress in MEMS-based transmission lines for use in microwave and millimeterwave range. MEMS-based transmission lines including different transmission line structure such as membrane-supported microstrip line microstrip line, coplanar microshield transmission line, LIGA micromachined planar transmission line, micromachined waveguides and coplanar waveguide are discussed. MEMS-based transmission lines are characterized by low propagation loss, wide operation frequency band, low dispersion and high quality factor, in addition, the fabrication is compatible with traditional processing of integrated circuits (IC’s). The emergence of MEMS-based transmission lines provided a solution for miniaturizing microwave system and monolithic microwave integrated circuits.

Keywords: millimeterwave, microelectromachining system, transmission line, monolithic microwave integrated circuits

1. INTRODUCTION
Microwave/millimeterwave bands are mainly used in the radar, missile guidance and electromagnetic countermeasure and space electronic technology, in addition. They are a preferred technology to realize the new concept miniaturized weapon or miniaturized elements in space electronic system. Microelectromechanical system (MEMS) technology presents the highest level of miniature Integrated Circuit (IC) system, which integrates with other planar devices of microwave and millimeterwave front-end subsystem. It is easy to form compact three dimensional microwave multiplayer circuit, so it can be used to the situation that volume, weight, power consumption and reliability are strictly confined, such as communication, radar, control and electromagnetic countermeasure (EMC), space technology and measurement system. The MEMS-based transmission line is fundamental element which can realize the MEMS passive and active circuits in Microwave Integrated Circuit (MIC) and Monolithic Microwave Integrated Circuit (MMIC) used in microwave/millimeterwave subsystems. Traditional planar transmission line structures for microwave circuit exhibit serious attenuation characteristics as the frequency increases, furthermore, the Q-factor of the transmission line declines quickly. This paper describes state-of-the-art MEMS-based transmission lines which demonstrate the characteristics of low transmission dissipation, broadband and low dispersion. More importantly, these MEMS-based transmission lines were fabricated using standard silicon MEMS foundry service compatible with traditional IC’s technology.

2. TYPICAL MICROMACHINED TRANSMISSION LINES STRUCTURES

2.1 Membrane-supported microstrip line
Membrane-supported microstrip line is a nondispersive transmission line which is suspended on a thin dielectric membrane via silicon micromachining techniques. The line geometry is similar to traditional coplanar waveguide (CPW) structure but situated above a metallized, air-filled cavity, as shown in Figure 1. Since the Membrane-supported microstrip line is surrounded entirely by air, its range of possible impedances encompasses higher values than those of traditional substrate supported lines. Typically, Membrane-supported microstrip line can be designed to realize characteristic impedances ranging from around 50 Ω to as high as 300 Ω. For filter and other planar circuit applications, it is more logical to work with a higher central impedance than the nominal 50 Ω. The fabrication of this structure applies bulk micromachined technique. In this transmission line the thin dielectric slab is made up of 3 layer materials (SiO₂/ SiN/ SiO₂) that support thin film deposited on a high resistivity bulk silicon substrate using thermal oxidation and high-temperature chemical vapor deposition. After the membrane is deposited, the transmission line strip is defined on the topside of the substrate. This is accomplished by first depositing a seed layer of gold via evaporation, then depositing additional gold via electroplating to satisfy skin depth thickness requirements, and finally defining the stripe using traditional photolithography. Figure 1 shows a bulk micromachined microstrip transmission line fabricated using this approach. Because the microstrip metal trace is supported by a microthining low-dielectric constant membrane, the line is very close to being homogeneous. This results in
the propagation of nearly TEM modes, virtually negligible dielectric loss, and an extremely wide single-mode propagation bandwidth.

2.2 Microshield transmission line
A shortcoming of the membrane-supported microstrip transmission line is that since it possesses no intrinsic ground plane, the structure must be placed on top of another metallized substrate. This requires some form of assembly process, such as soldering or fusion bonding, which makes the application somewhat complicated. Therefore, it is desirable to consider alternate line structures. Such an alternative is the coplanar microshield transmission line, as shown in Figure 2. The coplanar microshield transmission line is an extension of the membrane-supported line in that the membrane is now populated by the center conductor and ground planes. The central strip width $S$, the center-stripe-to-ground-plane gap $W$, and the ground plane-to-ground plane distance $G$ can be defined photolithographically on the top surface. The additional purpose of a metallized lower shielding cavity is to shield signal crosstalk between adjacent lines (hence the name microshield is given) and to eliminate radiation into parasitic substrate modes. The top and bottom ground planes can be directly connected because the inner surface of the micromachined bulk is metalized. This is advantageous compared to traditional microstrip and coplanar line in that it renders via holes or air bridges to connect to ground unnecessary. The performance of microshield transmission lines has been characterized in terms of their attenuation characteristics. Figure 3 gives experimental and theoretical results, which compare the performance of microshield and traditional coplanar transmission lines. The measured results showed that the performance is the same as traditional coplanar transmission line at lower frequencies. At high frequencies, such as millimeterwave wavelength range, the line displayed no dielectric-related loss as well as nondispersive, single-mode propagation. Figure 4 shows the measured effective dielectric constant of two types of microshield structures. The measured dielectric constant is very close to unity, which indicates a high degree of success in eliminating the substrate from underneath the line. The fact that the $\varepsilon_{\text{eff}}$ is not exactly with frequency, as is it be expected for an inhomogeneous dielectric.

2.3 Top-side-etched coplanar waveguide
The micromachined fabrication of both membrane-supported microstrip line and microshield transmission lines require many photolithographical masking steps as well as wafer bonding so that backside processing are not compatible with IC manufacturing processes. Reference 8 proposed a novel transmission line structure, whose fabrication avoids backside processing, which utilized top-side etching bulk micromachined to fabricate coplanar transmission lines on a standard CMOS process. Figure 5 shows the structure. Figure 6 displayed the measured performance, before and after etching.

To determine the effectiveness of elimination of the substrate from underneath the silicon lines, insertion loss and effective dielectric constant measurements of the transmission line were conducted. At 20GHz the insertion loss is decreased 24dB while at 40GHz a 34dB improvement was found. This improvement is not just due to elimination of substrate losses; there is reduction in metallic ohmic losses.

2.4 LIGA micromachined planar transmission line
The LIGA fabrication process allows the creation of tall (10 $\mu$m to 1mm) metal structures with steep (high aspect ratio) sidewalls on an arbitrary substrate material, as shown in Figure 7. These easily realized attributes of LIGA micromachined structures are shown in Figure 9. In this structure, very deep electromagnetic coupling effect was found. This feature can be used to certain passive microwave functions for strong-coupling circuits, or high-power handling capabilities for monolithic transceivers. The LIGA micromachined fabrication process steps are described in Figure 8.

2.5 Micromachined waveguides
The use of micromachining technique leads to the development of a micromachined waveguide. Despite the economies of the processed planar fabrication, the lowest microwave loss achievable in these technologies is ultimately limited by not only radiation losses but the unfavorable volume-to-surface area ratio, that is, low Q, characteristic of thin planar structures. These inherent limitations of planar technologies tend to make designers to a choice of low-loss metal waveguide components. However, traditional machining processes is used in the manufacture of metal waveguide components, that is, metal-cutting, which are based on materials such as brass, and which become difficult and expensive to apply as the dimensions of the components shrink, for example in a dimension of less than 0.3mm by 0.15mm for a 500–1000 GHz waveguide tube. Since micromachining techniques are perfectly capable of defining three-dimensional structures, it is appealing to use the idea of applying them to make waveguide components on a substrate in a planar process. These efforts have been made by applying bulk micromachined to fabricate rectangular waveguides for frequencies between 100 GHz and 1000 GHz on a silicon substrate. The measured insertion loss on a micromachined waveguide is of 0.04 dB per
wavelength across the 75~110 GHz band. This is comparable to the 0.024 dB per wavelength value of bulk micromachined-based integrated planar waveguide circuit fabrication.

3. CAD DESIGN METHODOLOGY FOR MICROMACHINED TRANSMISSION LINES

As a usual, micromachined transmission line is three-dimensional structure. Some two dimensional electromagnetic simulation software analyses is not effective to some structures. Three dimensional finite element method (3D-FEM) is effective analysis method in the design of MEMS devices\textsuperscript{13}. Reference 14 adopts finite element method to analyses characteristic impedance under different structure with different dimensions. Calculated result illustrated that the influence of the dimension parameters to characteristic impedance comes mainly from the width of signal line and the air gap between signal line and ground line. This conclusion will offer basics consideration to micrometer-level transmission line fabrication. At this moment, some MEMS modeling and computer simulation tools have been developed\textsuperscript{15,16}. Some CAD tools address specific demands, e.g. 3D analysis like OYSTER, MEMCAD, etching like ASEP. In the design of transmission lines, full-wave EM simulation, the HP’s Momentum is used. Numerical simulation for high frequency behaviour using MoL (Method of Lines) and TLM (Transmission Line Method) methods shows very good agreement to measured results, so that the elements extraction of accurate equivalent circuit in the time-domain analysis can be realized. The model parameters is obtained to fit the S-parameter simulated from full wave electromagnetic simulation, the Ansoft HFSS. The current CAD environment provides a complete design flow for system designers, however, the integration of tools used by device designer is still being investigated. The micromachined technique will benefit greatly from the CAD analysis methods to predict the performance.

4. APPLICATION OF MILLIMETER-WAVE TRANSMISSION LINES

The high performance RF element and system is made by micromachined process techniques, which is used widely in microwave and millimeterwave fields, such as low loss transmission line, passive element, reconfigure filter, antenna, switch, high Q medium resonator\textsuperscript{17,18} and other active devices\textsuperscript{19}. Planar inductors and capacitors can be used to frequency band up to 60 GHz and higher and still have exactly the same geometries as their counterparts on silicon or GaAs substrates and such technique can apply lump element of planar waveguide transmission lines\textsuperscript{20}. Reference 21 proposed an aperture-coupled micromachined microstrip antenna, which offers a novel approach to vertical integrated array antenna of millimeterwave frequency band. The shielded membrane microstrip (SMM) has been used to realize high performance planar components for applications up to 110 GHz millimeterwave range, which is compatible with MMIC technique\textsuperscript{22}. In some applications, for example, the deep-coupled line requires thicker strip or three-dimensional structures for directional coupler design. LIGA process utilizes deep X-ray lithography, electroplating and molding to make thick structures. Using LIGA micromachined process technique can make high-aspect ratio metal structures and enable the development of high-power monolithic circuits as well as couplers and filters that require very high coupling\textsuperscript{23}. The Korea Kwangwoon university developed broad band, low loss LIGA millimeterwave bandpass filters\textsuperscript{24}, as shown in Figure 11. Tested results of the prototype exhibit the minimum insertion loss is 1.7dB at the center frequency of 33.2GHz, and the bandwidth is about 40%.

CONCLUSIONS

The MEMS-based transmission lines for microwave/millimeterwave systems can be designed to provide performance in combination with low insertion loss and small size. Such transmission lines have a good performance in millimeterwave frequencies. The micromachining technique is compatible with all types of transmission lines, such as the microstrip, the coplanar waveguide and the stripline guide media. Furthermore, it can be used with standard MMIC fabrication or for high quality surface mount elements and subsystems. For LIGA micromachined transmission line, it can be used in the higher power MIC and suitable for MMIC transmitter. It is undoubted that MEMS-based transmission lines will play a key role in microwave/millimeterwave range applications in future. With further advancements being made in micromachined fabrication, the MEMS-based transmission lines can achieve higher performance levels with a competitive manner in microwave/millimeterwave systems.

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REFERENCES


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Figure 1 Membrane-supported microstrip transmission line

Figure 2 Microshield transmission line geometry

Figure 3 The attenuation for different transmission lines

Figure 4 Tested effective dielectric constant on two microshield lines

Figure 5 Cross-sectional view of top-side-etched coplanar waveguide transmission line

Figure 6 Measured results of top-side-etched coplanar waveguide transmission line before and after etching. (a) Attenuation; (b) Effective dielectric constant (real part); (c) Effective dielectric constant (imaginary part).
Characteristic impedance ($\Omega$)

Plated Metal

Ground

Plated Dielectric Substrate

Width $W$ ($\mu$m)

300 $\mu$m thick sheet PMMA

1 $\mu$m thick spun on PMMA

Figure 7 LIGA planar transmission-line

Figure 9 Characteristic impedance data for LIGA microstrip line

Figure 8 Cross sections of the LIGA fabrication process:
(a) application of a plating base; (b) application of sheet resist; (c) X-ray exposure of resist; (d) conductor electroplating; and (e) final structure

Figure 10 Cross-section view of the waveguide fabrication process

Figure 11 SEM picture of the prototype

Figure 12 Filter topology
Table 1 Parameters illustration of figure 3

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