Micromachined Transmission Lines for Millimeter-Wave Applications

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Abstract

Several different fabrication techniques and materials have been proposed for making low loss high performance micromachined transmission lines. In this paper a review of several micromachined transmission lines that have been proposed over the last years are classified into four types according to their physical structure and their power losses addressed.

1. Introduction

The RF/microwave circuitry of a wireless system requires the integration of several components such as antennas, filters, amplifiers, phase shifters and switches. In general, microsystems for radio frequency, also known as RF-MEMS offer several advantages over traditional technologies, such as, major integrability, reconfigurability, tunability, high Q values, low losses, higher linearity, and low energy consumption [1]. The key of a micromachined transmission line is to obtain good loss performances while also other aspects as their integrability with other components, the feasibility and fabrication method used for its development are important issues. Several structures have been proposed and are summarized here. Many of them are compared in loss performance. The basic structure of an RF/microwave system is the transmission line, hence several efforts have been done to obtain low loss, low dispersion transmission lines for millimeter-wave applications. Dispersion and radiated losses depend on the structural form of the transmission line. Losses associated with the materials used are related to the conductivity of the metals, the loss tangent of the dielectric materials, and the resistivity of the semiconductors.

The dimensions of RF/microwave circuits are inversely proportional to their operational frequencies, that is, at higher frequencies circuits become smaller. For this reason at millimeter-wave frequencies, fabrication tolerances become a critical factor for which micro-fabrication techniques are employed considering the mechanical and electrical properties of the materials.

Planar transmission lines suffer from high conductor losses at millimeter-waves, where it is well known that the surface resistance of the conductor increases directly proportional to the square root of frequency. Therefore by using micromachined transmission lines, one of the goals is to achieve wide conductors to provide good current distributions, lowering the overall conductor losses of the structure, of course depending on the physical shape of the transmission line. Also the use of low dielectric constant substrates with low loss tangents can be used to achieve the wide conductors, where the main preference is to have an air propagation media, where wide conductors can be achieved while having low propagation losses. Enclosed or shielded transmission lines present no radiation losses.

In this paper a summary of the performance, the dimensions and materials used in several types of transmission lines is presented. The losses in the following examples will be given as the unloaded quality factor of a $\lambda/2$ resonator at the given frequency for each case unless otherwise mentioned.

2. Fabrication techniques and structures of transmission lines for millimeter wave frequencies

This section is divided in four subsections, where micromachined transmission lines are classified into four categories, which are, waveguide transmission lines, microstrip transmission lines, coaxial type transmission lines and coplanar transmission lines.

2.1 Micromachined waveguide transmission lines

In Figure 1 [2] a cavity resonator is presented that has an unloaded Q at X band of Q_o=506. The feed lines are electroplated on a 500μm thick silicon wafer and are coupled to the cavity via thru-holes. The cavity is fabricated using silicon anisotropic etching and then it is metalized with a 2μm thick metal.

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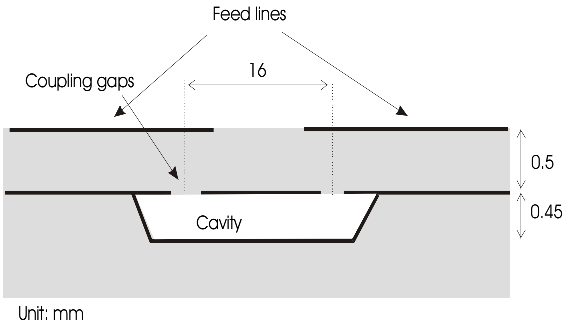


Figure 1. Cavity resonator at X band, taken from [2]

In figure 2 [3] a bulk silicon cavity is presented. This structure consists of stacked low resistivity silicon wafers. The silicon wafers are previously etched such that the inner cavity is formed. Finally all the etched wafers are aligned and the whole structure metalized. For this structure, the resonant frequency is 29.3GHz, for which a quality factor of Q_o=4520 was measured.

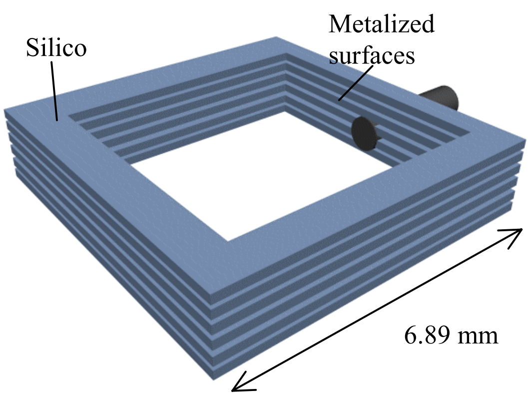


Figure 2. Micromachined silicon cavity without top cover, taken from [3]

In [4] diamond shaped waveguides made by EDP anisotropic etching of silicon are presented, this transmission line is proposed for operation at W band.

2.2 Micromachined microstrip transmission lines

Silicon is a material that presents adequate mechanical characteristics for micromachining and has been widely exploited for RF MEMS applications. It is important to note that low resistivity silicon (10 Ohm x cm) has not yet been used effectively in micro-machined circuits. However, high resistivity silicon (1000 Ohm x cm) presents higher material costs but it is widely used in circuits.

Figure 3 [5] Shows a transmission line made in silicon. This is an inverted microstrip line that has air between the dielectric and the ground plane as principal propagation media. BCB (Benzocyclobutane) dielectric is used to reduce the losses in the transmission line as it prevents direct contact between the transmission line and the silicon.
This transmission line exhibits an unloaded quality factor of Q_o=60 at 40 GHz. However, if the silicon layer is removed, and only BCB supports the line, this Q increases to Q_o=110.

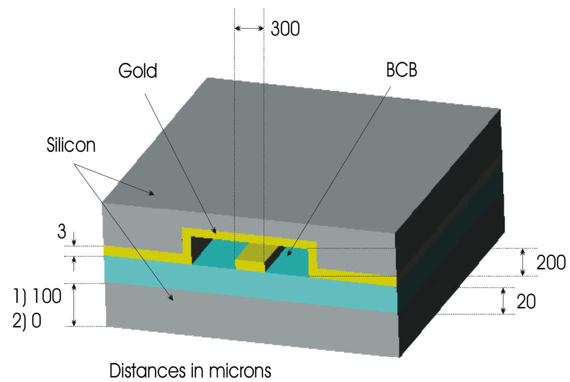


Figure 3. Inverted microstrip, taken from [5]

Another widely used transmission line is the one shown in figure 4 [6]. This structure has good performance at millimeter waves since the propagation material is composed mainly of air. Another advantage is that the structure is completely enclosed so the radiation losses are minimum. In this configuration, most of the wave is propagated in air so the losses are mainly due to the metal, hence it exhibits a high Q_o=450 at 60 GHz.

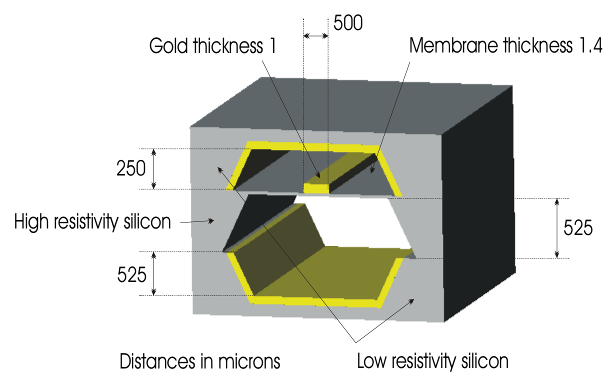


Figure 4. Microstrip over silicon membrane taken from [6]

The structure in figure 5 [7] is similar to the one in figure 4 but a photosensitive resin (SU8) has been used instead of silicon due to its lower costs and its easier manufacturability. This resonator has a Q_o=130 at 29 GHz.

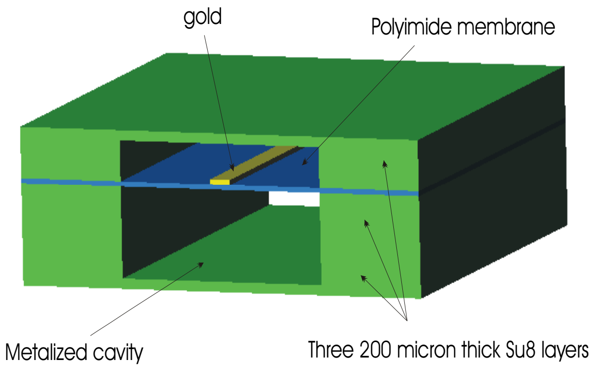


Figure 5. Microstrip over membrane using a SU8 shield, taken from [7]

A suspended post transmission line has been proposed in [8], shown in figure 6, where a microstrip is supported on 7 or 10 micrometers tall dielectric posts over a ground plane, this structure presented a 1.5 dB/cm loss at 50 GHz, considering a 10 micrometers tall dielectric post.

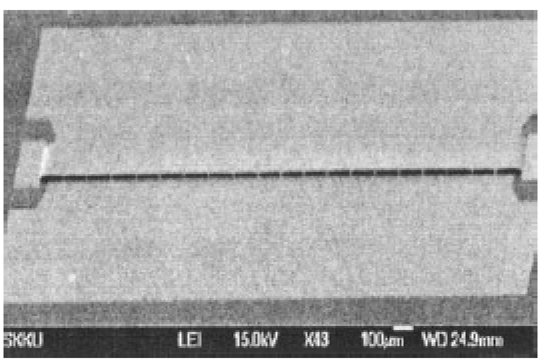


Figure 6. Photograph of the dielectric post microstrip line (DAML), taken from [8]

2.3 Micromachined coaxial type filters

A dielectric filled coaxial transmission line is presented in [9], and shown in figure 7. This coaxial line has potential operation in the terahertz region, and as it is MMIC compatible, it presents the possibility of having no crosstalk between adjacent lines, which enables denser IC design. The square coaxial transmission line had a measured loss of 1.5 dB/mm at 35 GHz, and a predicted loss of 6.4 dB/mm at 1 THz using a 4 micron width centre conductor, and a predicted loss of 3 dB/mm at 1 THz using a 10 micron width centre conductor.

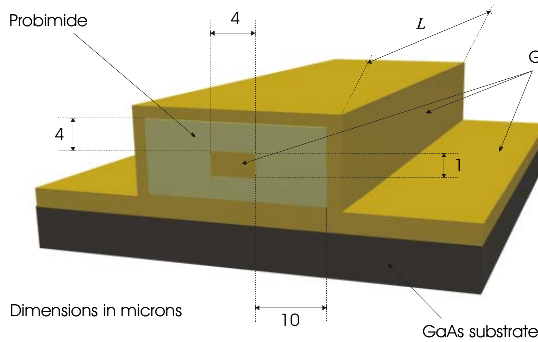


Figure 7. Dielectric filled coaxial transmission line taken from [9]

The structure in figure 8 [10, 11] is a suspended coaxial line. This line is held by λ/4 stubs connected to the metal side walls, which allow the complete removal of lossy dielectrics. This line shows a Q_o=210, at 29.75 GHz. This transmission line has been made by laser micromachining, and also its fabrication with SU8 has been devised, where SU8 allows complex structures to be realized.

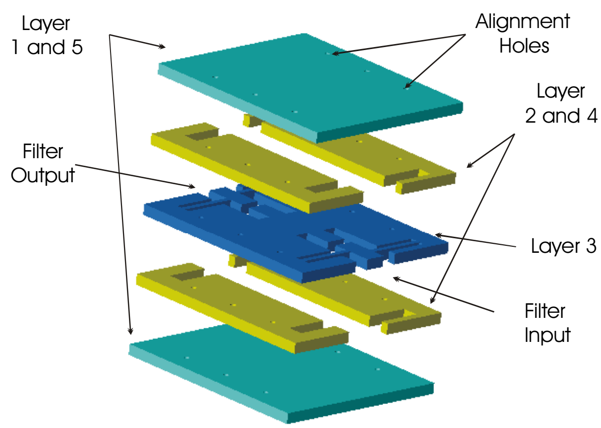
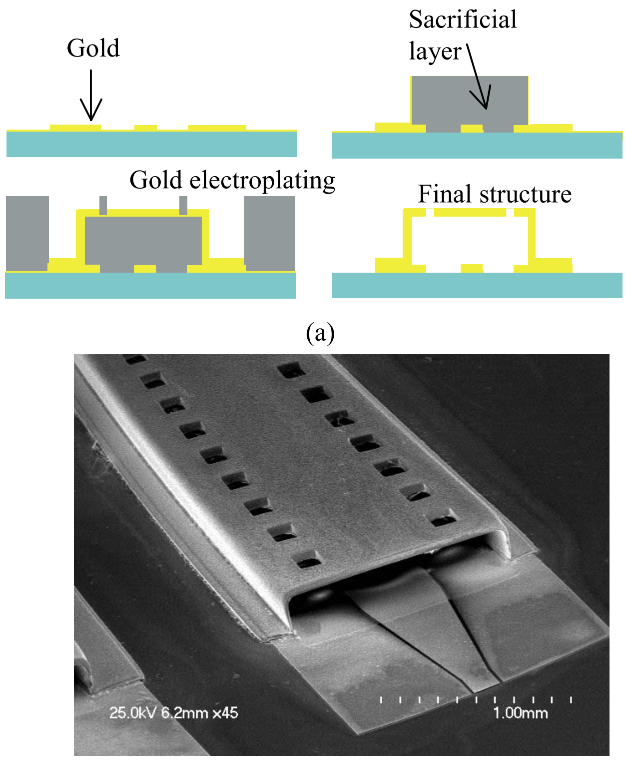


Figure 8. Suspended coaxial transmission line taken from [10]

The structure in figure 9 [12], consists of a monolithic surface micromachined half-coaxial transmission line. For this structure, JSR THB-151N photo-resist was used, which consists of a half coaxial cavity on a quartz substrate, in the final structure the sacrificial layer is removed leaving a 100 µm air propagation media between conductors. The quality factor for this structure is Q_o=153 at 31.78 GHz.



(b)

Figure 9. Half coaxial transmission line, (a) fabrication process, (b) photograph, Taken from [12]

A process called EFAB^{TM}, shown in figure 10, has been developed to produce integrated coaxial structures [13], where the process consists of multiple deposition and planarization of metal layers, this process can be used to achieve complex 3D structures.

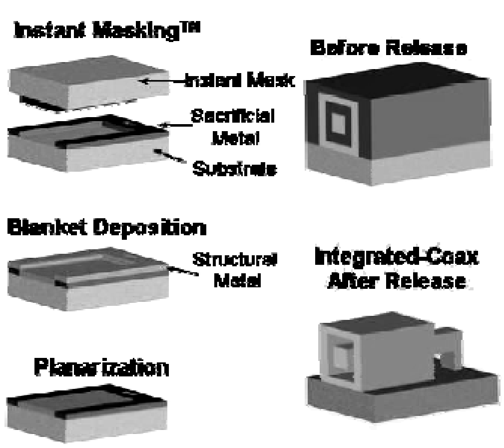


Figure 10. Process flow for the selective electrochemical metal deposition (EFAB^{TM}) taken from [13]

2.4 Micromachined coplanar transmission lines

Coplanar lines concentrate most of the electromagnetic fields near the surface between the center and ground conductors. For this reason, in figure 11 [14] a coplanar line is presented where the substrate near the lines was removed to reduce the losses and decrease dispersion. The unloaded Q of this structure is Q_o=47 at 60 GHz. If the same line is designed without removing the silicon between the lines the Q decreases to Q_o=33.

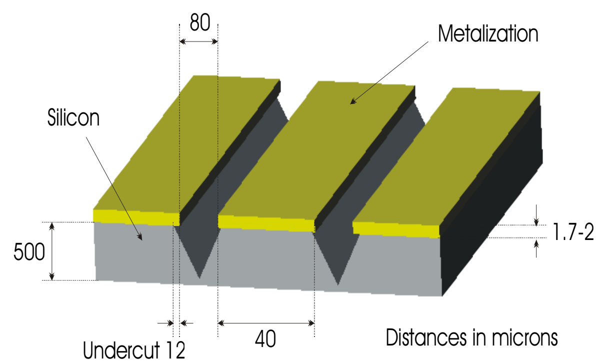


Figure 11. Coplanar micromachined transmission line taken from [14]

In figure 12 [15] the transmission line is manufactured over a thin SU8 membrane for W band (75-110GHz) operation, the structure is supported on a glass substrate which is later removed. Its Q is Q_o=120 when it is shielded and it reduces to Q_o=60 if the shielding is removed.

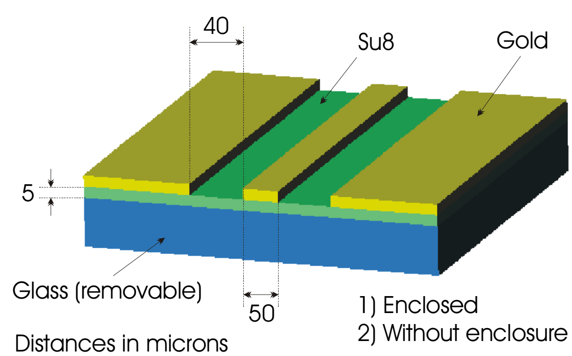


Figure 12. Coplanar transmission line over SU8 membrane, taken from [15]

The transmission line of figure 13 uses micromachining technology to lift the center conductor [16] hence reducing dielectric losses. This structure presented an unloaded Q of Q_o=36 at 50 GHz.

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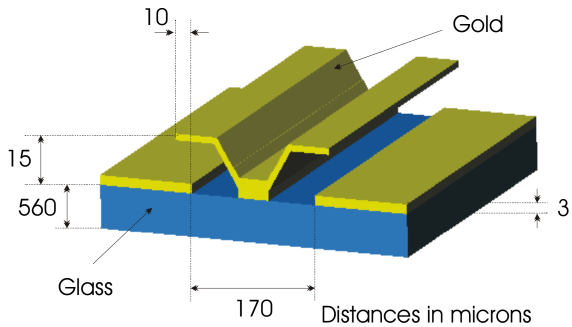

Figure 13. Coplanar transmission line over
A glass substrate, taken from [16]

The structure in figure 14 [17], is a coplanar waveguide on SU8, where the SU8 has been removed in the space between conductors, to reduce the losses of the silicon substrate and the SU8. This transmission line presented a loss of 0.18 dB/cm at 20 GHz.

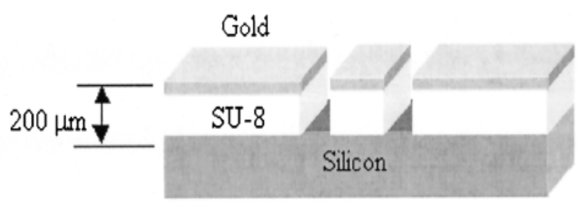

Figure 14. Coplanar transmission line on SU8
taken from [17]

3. Conclusions

Micromachining techniques offer the advantages of low loss structures at millimeter waves. In this paper a review of several transmission line types was presented. From the review it can be seen that waveguide cavities and optimized microstrip cavity structures present the lowest losses, where they present an air propagation media and they are fully enclosed to avoid radiation losses. Other type of proposal for low losses is the coaxial type filters which are more compact in size for a given frequency and impedance compared to the waveguides and microstrip cavity structures, providing a completely or partially shielded structure avoiding radiation. And finally the coplanar transmission lines were presented, which tend to have higher losses compared with the waveguide and microstrip cavity structures, mainly because of their current distribution, but have the advantage of having a completely planar transmission line. The appropriate choice of a transmission line will be a tradeoff between the loss performance, cost, complexity of the fabrication process involved and its integration with other components for a given system. For microwave filters a high Q is always desirable, in order to get good insertion loss performance, and good out of passband rejections for a given filter specification.

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