A MILLIMETER-WAVE MICROMACHINED LOWPASS FILTER USING LUMPED ELEMENTS

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Abstract - A new approach is presented for realizing millimeter-wave micromachined lowpass filters using lumped elements. An efficient quasi-static analysis is utilized to design a Ka-band filter with 0.5 dB insertion loss and a rejection bandwidth from 30-125 GHz. The layout requires ten times less area than a comparable stepped-impedance implementation.

I. INTRODUCTION

Micromachined transmission lines supported by thin dielectric membranes have proven to be high performance alternatives for millimeter-wave applications. A membrane-supported microstrip has been used to develop components such as spiral inductors with low parasitic capacitance [1] and W-band coupled-line bandpass filters [2]. The microshield geometry (Figure 1) is a membrane-supported coplanar waveguide that has been demonstrated at Ka-band [3], W-band [4], and up to 250 GHz [5]. The strengths of these monolithic architectures derive primarily from the homogeneous air dielectric, and include broad bandwidth, minimal dispersion, and zero dielectric loss.

Certain aspects of the membrane lines, however, present potential difficulties for component design. The two primary challenges are realizing physically compact structures and achieving a low characteristic impedance. Due to the low permittivity substrate, the line lengths on a membrane are approximately 2.5 times longer than equivalent circuits on silicon or GaAs. For the same reason, it is more difficult to achieve a low characteristic impedance using membranes lines than it is with Si or GaAs. These factors have a significant impact on the design of circuits such as lowpass filters.

Typically, microwave lowpass filters are implemented using the distributed inductance and capacitance of individual transmission line sections. The most common variation is the stepped-impedance approach, in which a combination of high- and low-impedance transmission lines are placed in series. Examples of this technique have been realized using microshield at Ka-band and W-band [2, 3], with suspended strip-line at C-band [6], and in a compact alumina CPW design at C-band [7]. On low permittivity substrates, the line lengths in these filters are relatively long and the low impedance sections are wide. Furthermore, an accurate design for mm-wave frequencies requires a rigorous characterization of the parasitics at the impedance steps [2]. An implementation which can reduce these problems is one that utilizes shunt, open-circuit stubs [8]. While this approach has advantages, the shunt stubs result in wide circuit dimensions.

In this paper, a new technique for millimeter-wave circuit design using lumped elements is employed to develop a micromachined lowpass filter. The configuration consists of series short-end stubs [9] and MIM (metal-insulator-metal) overlay capacitors (Figure 2). It will be shown that the approach leads to designs that are compact in length and width, have low insertion loss and a broad rejection band, and can be accurately analyzed using an efficient quasi-static method.

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II. FILTER DESIGN

The design procedure centers on the use of an equivalent circuit model for the series stub and a subsequent quasi-static analysis of the entire filter layout. Because the geometry is electrically small with minor discontinuities, and due to the broad-band TEM propagation of the microshield line, this approach provides a very accurate and efficient means of characterizing the filter performance.

In the initial step, an equivalent circuit for the short-end stub is obtained using the model shown in Figure 3. The scattering parameters for the stub are first calculated by treating each half of the laterally symmetric geometry as two coupled lines, and applying a version of the 4-port quasi-static analysis outlined by Jones and Bolljahn [10]. The even and odd mode impedances, which exhibit little variation over frequency, are found using the spectral domain approach [11]. With the calculated S-parameters, a commercial circuit optimizer is then used to extract the equivalent circuit element values. The model is very accurate for stub lengths up to at least 45 degrees, and scales linearly with stub length.

The design proceeds by selecting a lowpass filter prototype [12] and determining the required stub lengths and MIM capacitor values. To demonstrate, a 5-section 0.075 dB ripple Chebyshev response with a cut-off frequency at 27 GHz was chosen. The circuit layout consists of four stubs arranged in series with MIM capacitors, with the 2^{nd} and 4^{th} stubs reversed (Figure 4); a 5-element filter can be defined from this layout by neglecting capacitors C_s and C_{p1}, which are an order of magnitude smaller than C_{p2}. The stub lengths are selected to obtain the series inductance, and C_{MIM} is set by using the shunt combination with the resultant C_{p2} to obtain the required capacitance. In this example, L_T=700 μm (L_s=0.42 nH) for each stub, C_{p2}=31 fF, and C_{MIM}=37 fF.

The final step in the procedure involves design optimization using the quasi-static analysis mentioned above. Although the circuit model simplifies the design process, it is limited in two respects: it is not accurate at frequencies well into the rejection band, and the location of the MIM capacitors cannot be varied. The quasi-static analysis, however, compares well with full-wave analysis of the stubs up to nearly the *second* ($\lambda/2$) resonance, and allows the location of the MIM capacitors to be arbitrarily specified. As shown in Figure 5, the predicted responses from the circuit model and the quasi-static analysis agree nearly exactly up through 45 GHz. For this comparison, the capacitors are positioned at the ends of the stubs (L_1=L_T). By moving the capacitors, the stop-band of the filter can be greatly improved without affecting the pass-band performance; these results are illustrated in Figures 6 and 7. This optimization using the coupled line analysis requires minimal computational effort.

III. RESULTS AND DISCUSSION

A microshield lowpass filter based on the 0.075 dB Chebyshev design was fabricated and measured from 5-40 GHz. A comparison between the measured performance and the quasi-static analysis is shown in Figure 8; the measured pass-band insertion loss is less than 0.5 dB up to 20 GHz and the loss factor $(1-|S_{11}|^2-|S_{21}|^2)$ is less than 0.1 up to 20 GHz, peaking at 0.15 at 25 GHz. The predicted response shows that the second pass-band does not occur until 125 GHz.

The characteristics of this filter have many advantages in comparison to alternative implementations. For example, the dimensions of the filter shown in Figure 2 are 300 μm (wide) by 2800 μm (long); a comparable 5-section stepped impedance microshield filter with identical pass-band characteristics was nearly two times as long, five times as wide, and had a second pass-band at 80 GHz [3]. In addition, a variation of this new approach was considered that involved replacement the low impedance sections in a stepped impedance design with MIM capacitors. This is conceptually simple, but the actual implementation was found to result in a large shunt inductance which degraded the pass-band response and was not easily corrected.

The concept of integrating lumped elements into millimeter-wave distributed circuits has been demonstrated in the realization of a compact low-pass filter. The technique can be applied to a variety of circuit geometries, and the use of a compact stub design (e.g. [13]) with the MIM capacitors is currently being pursued.

ACKNOWLEDGEMENT

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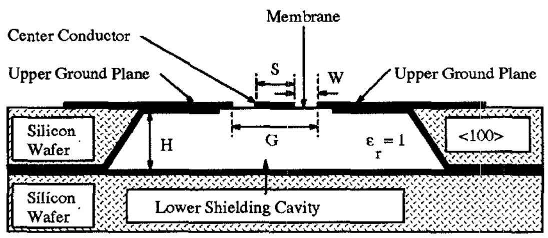

Figure 1: Cross-sectional view of the microshield transmission line geometry.

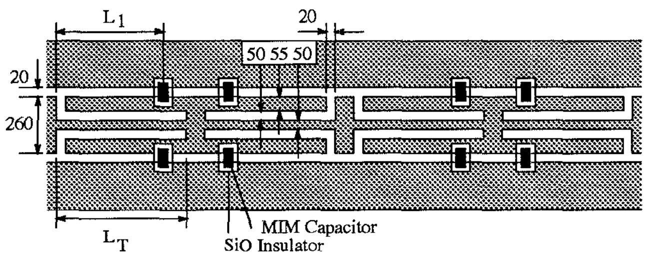

Figure 2: Metallization pattern for the microshield 5-section lumped element lowpass filter (dimensions in μm).

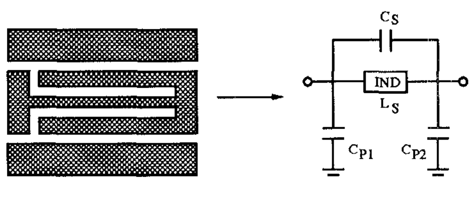

Figure 3: Equivalent circuit model for the series short-end stub.

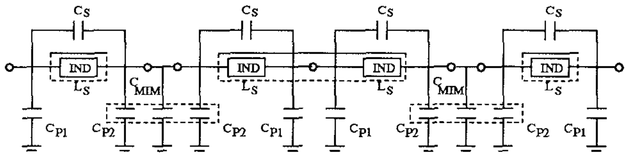

Figure 4: Equivalent circuit model for the 5-section lowpass filter (each section is enclosed in a box). C_S and C_{P1} are neglected in designing the filter.

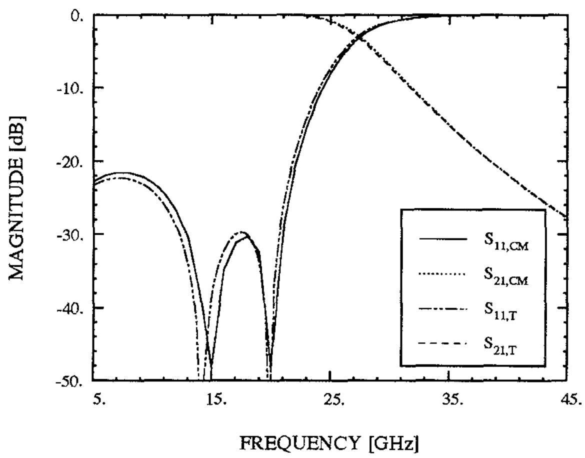

Figure 5: Calculated scattering parameters for a lowpass filter of the type shown in Figure 2, for $L_1 = L_T = 700\ \mu m$ (CM = circuit model, T = quasi-static analysis).

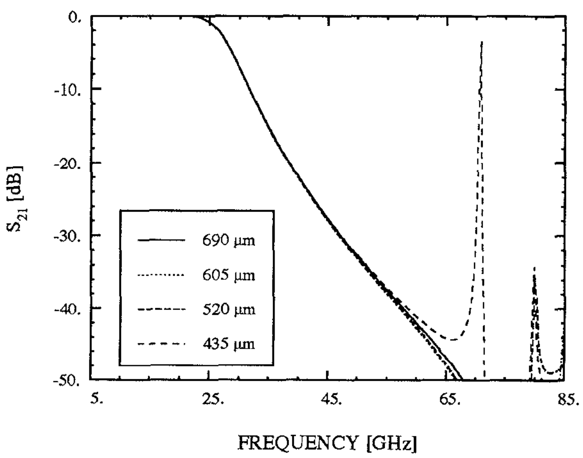

Figure 6: Calculated S_{21} for a lowpass filter of the type shown in Figure 2, for different values of L_1 (microns).

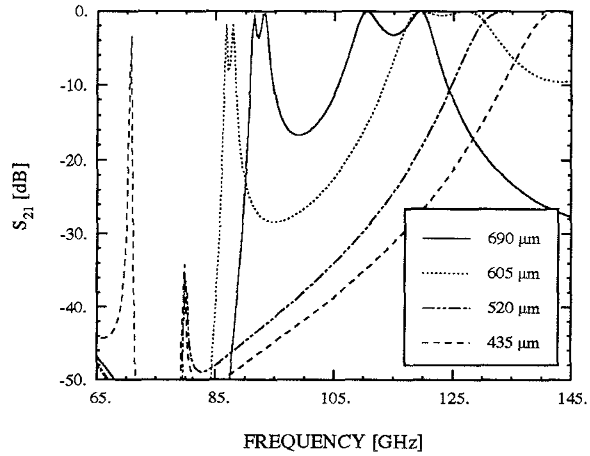

Figure 7: Calculated S_{21} near the second passband for a lowpass filter of the type shown in Figure 2, for different values of L_1 (microns).

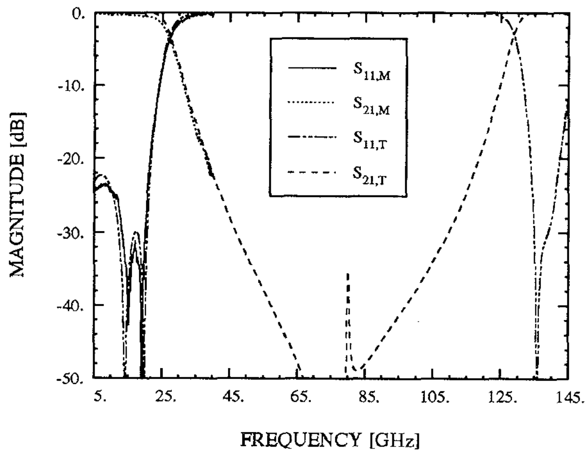

Figure 8: Scattering parameters for a lowpass filter of the type shown in Figure 2, for $L_1 = 520\ \mu m$ (M = measured, T = quasi-static analysis).