Compact Low-Loss Monolithic CPW Filters Using Air-Gap Overlay Structures

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***Abstract*—In this letter, two types of compact low-loss monolithic coplanar waveguide (CPW) filters using air-gap overlay structures are presented. Vertical stacking in overlay structures offers size reduction. Furthermore, air-gap overlay structures do not require additional dielectric process and are free from dielectric losses. An X-band bandpass filter using air-gap overlaid artificial transmission lines showed 67% size reduction. A stepped-impedance low-pass filter using highly separated metal-air-metal (MAM) capacitors as low-impedance lines achieved not only siz, but also loss reduction. Small size, low loss, and simple process steps make the air-gap overlay structures very promising for monolithic CPW passive devices such as filters.**

***Index Terms*—Air-gap overlay structure, compact filter, coplanar waveguide.**

I. Introduction

COPLANAR waveguide (CPW) technology has gained popularity in the design of microwave and millimeter wave circuits due to integration capability with the active devices and simple process steps avoiding wafer thinning and via holes. However, complicated passive components such as filters still suffer from large size when applied to MMICs. One way to solve this problem is to employ multi-layer vertical stacking using thin film dielectric spacers [1]–[3]. This, however, requires additional thin film process and thus results in non- negligible dielectric losses at high frequencies.

This paper presents compact X-band bandpass and low-pass filters realized with air-gap overlay structures, where air gap has been employed as inter-metal spacers instead of the dielectric films. Long CPW lines in the BPF have been replaced by short artificial transmission lines consisting of L–C networks, where air-gap overlay structures have been utilized as capacitors. Moreover, metal–air–metal (MAM) capacitors with large air gap (12 μm) have been applied to an X-band stepped-impedance LPF to demonstrate the low loss nature of the air-gap structures. Air-gap overlay structures offer low loss at high frequencies, size reduction and simple process without additional dielectric process steps.

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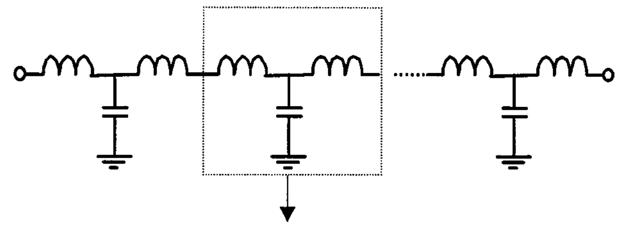

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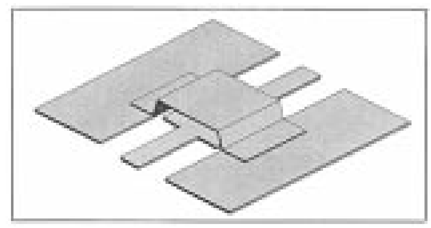


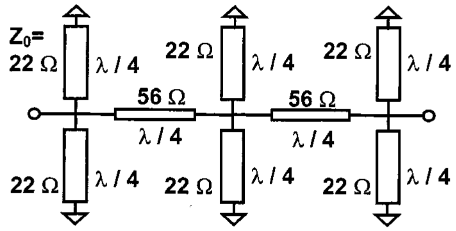
(b)

Fig. 1. (a) Lumped-element artificial transmission line consisting of periodic L/C-type low-pass networks. (b) Unit low-pass network realized with CPW lines and air-gap overlay structures.

II. Bandpass Filter

The bandpass filter of this work consists of multiple sections of $\lambda/4$ short-circuited shunt stubs and $\lambda/4$ series lines. To reduce the size of the filter, artificial transmission lines composed of periodic low-pass networks using lumped L–C elements shown in Fig. 1(a), have been substituted for the conventional CPW lines. The substituted lines are smaller in size, but show identical electrical properties up to a cut-off frequency, which is designed to be much higher than the pass band of the filter. The capacitor sections of the L–C network were realized with air-gap overlay structures, while the inductor sections were realized with CPW lines. The resulting semi-lumped line section is shown in Fig. 1(b).

Fig. 2 shows the equivalent circuit diagram using ideal transmission line and the photograph of the X-band three-section shunt stubs BPF, in which two semi-lumped lines with three low-pass unit networks are used for series lines and shunt stubs; low impedance (22 Ω) was used for short-circuited shunt $\lambda/4$ stubs while high impedance (56 Ω) was used for $\lambda/4$-long series lines. This resulted in 67% length reduction compared to the conventional CPW lines. The physical chip size is 4.7×5.3 mm^2, which could be made smaller if the lines were folded and the filter was fabricated on high-ε substrates such as GaAs. Low impedance (22 Ω) was chosen for shunt stubs due to high external Q-factor and narrow bandpass characteristics of low-Z_0 short-circuited shunt stubs. It is also worthwhile to note that



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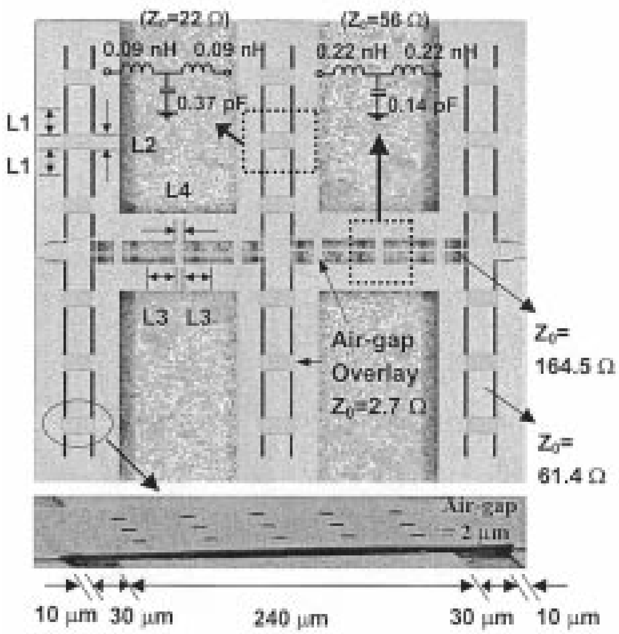


(b)

Fig. 2. (a) Equivalent circuit diagram using ideal transmission lines and (b) photograph of the X-band three-section shunt stubs BPF using air-gap overlay structures. The length of all lines of (a) is $\lambda/4$ at 10 GHz. Lumped elements equivalent circuits for two unit low-pass network lines are also included. $L1 = 292$ μm, $L2 = 200$ μm, $L3 = 267$ μm, $L4 = 75$ μm. The chip size is 4.7×5.3 mm^2 on quartz.

such a low impedance (22 Ω) cannot be achieved using conventional CPW lines because of photolithographical limit (slot width = 2 μm). It was possible in this work thanks to broadside coupling using air-gap overlay.

All the air-gap overlay structures and CPW lines were fabricated on a 520 μm-thick quartz substrate with a fixed ground-to-ground spacing of 320 μm. As shown in Fig. 2(b), the air-gap overlay structures used as capacitor sections were realized with an overlap width of 300 μm and a separation of 2 μm, which resulted in $Z_0 = 2.7$ Ω and $\varepsilon_{\rm eff} = 1.33$. Two different-impedance CPW lines were used for inductor sections; high-impedance lines (center conductor width = 20 μm, $Z_0 = 164.5$ Ω and $\varepsilon_{\rm eff} = 2.42$) were used for series lines and low-impedance lines (center conductor width = 240 μm, $Z_0 = 61.4$ Ω and $\varepsilon_{\rm eff} = 2.4$) for shunt stubs. The cut-off frequencies of the artificial lines were about 40 GHz, which was much higher than the pass band of the filter (10 GHz). The filter was fabricated using in-house micromachining techniques. The details of the fabrication process have been reported in our previous work [4]. Fig. 3 shows simulated and measured frequency response of the fabricated filter. Measured insertion loss was less than 2.3 dB and return loss was better than 25 dB at 9.5 10.8 GHz. Excellent agreement was found between simulation and measurement. The simulation was performed using a commercial EM simulator (IE3D).

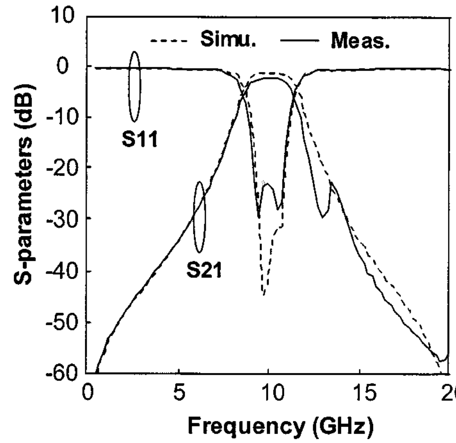
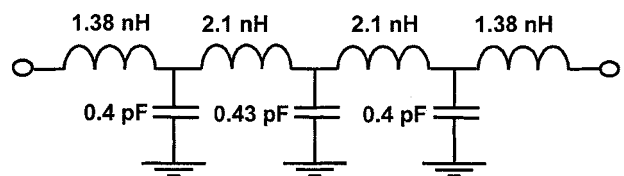
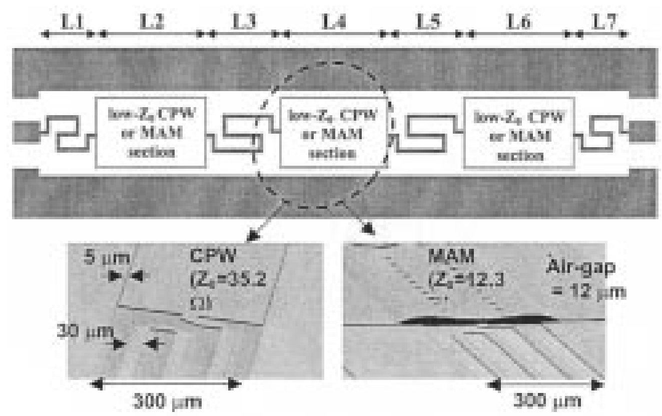


Fig. 3. Comparison of simulated and measured responses of the X-band BPF using air-gap overlay structures.



(a)



Filter type (Low Z_0)	L1 (L7) (μm)	L2 (L6) (μm)	L3 (L5) (μm)	L4 (μm)	Total chip size W x L (mm^2)
CPW	884	2766	1265	2958	0.9 x 12.8
MAM	884	1272	1265	1361	0.9 x 8.2

(b)

Fig. 4. (a) Lumped elements equivalent circuit and (b) schematic of X-band seven-section stepped-impedance LPF's. Photographs showing the details of the hi/lo-impedance sections of the fabricated MAM LPF and the conventional CPW LPF are also included.

III. LOW-PASS FILTER

In the air-gap overlay structures, the conductor loss decreases as the separation between overlapped conductors increases due

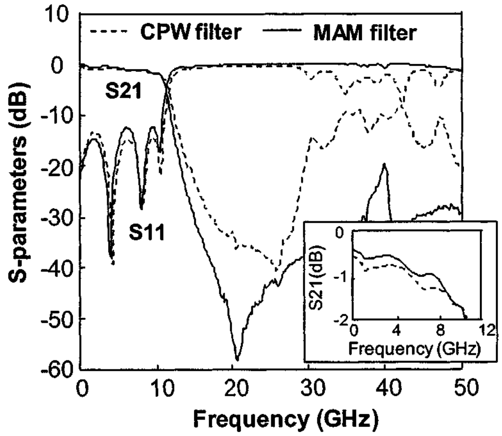


Fig. 5. Comparison of measured responses of the MAM LPF and the conventional CPW LPF.

to weaker electric field and lower current density at the conductor plates [4], [5]. It is thus expected that (MAM) capacitors with large air gap can be effectively used as low-loss capacitors. For experimental verification, X-band 0.5 dB equiripple Chebyshev seven-section stepped-impedance low-pass filters have been implemented using MAM capacitors and CPW lines on a 520 μm-thick quartz substrate. In both the MAM LPF and CPW LPF shown in Fig. 4, the inductive sections were realized, using meandered high-Z_0 CPW lines ($W = 30$ μm) with 0.64 nH/mm for size reduction, and were common to both filters. However, the capacitive sections for MAM filter were realized using MAM capacitors with a metal overlap width of 290 μm and a separation of 12 μm, resulting in $Z_0 = 12.3\ \Omega$ and $\varepsilon_{\rm eff} = 1.25$ while the CPW lines ($Z_0 = 35.2\ \Omega$ and $\varepsilon_{\rm eff} = 2.2$) with the same width of 290 μm were employed for conventional CPW filter. Therefore, the MAM lines resulted in 54% length reduction in capacitive sections of the filter according to Richard's transformation. Micromachining techniques using thick photoresist [4] were employed to achieve a high separation of 12 μm. Element values of the LPF were determined using a standard design procedure [6]. All the line elements were realized with ground-to-ground spacing of 300 μm. The transmission line parameters such as Z_0 and $\varepsilon_{\rm eff}$ of each section were calculated using IE3D.

The measured response of the MAM LPF is compared with that of CPW LPF in Fig. 5. Insertion loss improvement of 0.2 dB is observed at the center of the pass band (6 GHz), and high rejection (>20 dB) is obtained over multiple-octave bandwidth (14~50 GHz). In addition to the size reduction effect stated earlier, the LPFs using air-gap overlay structures present low losses, sharp skirt, and wide stop band characteristics.

IV. Conclusions

Air-gap overlay structures have been employed to demonstrate size reduction of X-band, bandpass, and low-pass CPW filters. Artificial transmission lines utilizing air-gap overlay structures helped to reduce the line lengths of the bandpass filter by as much as 67%. The low-pass filters using micromachined MAM capacitors with large separation (12 μm) showed reduced losses as well as smaller size compared with the conventional CPW LPFs. Air-gap overlay structures do not require additional dielectric process steps and, consequently, do not suffer from the dielectric losses. They are, therefore, well suited to compact, low-loss and low-cost passive circuit applications at microwave- and millimeter-wave frequencies.

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