Silicon RFIC UWB Bandpass Filter Using Bulk-Micromachined Trench Couplers

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***Abstract* — A low loss silicon RFIC UWB bandpass filter is reported. The filter exploits a novel metalized coupled trench structure, fabricated by advanced silicon bulk micromachining. The couplers can achieve more than -2 dB coupling, with good even-odd mode phase velocity balance, while having practical dimensions. The CPW filter is designed using well-known interdigital filter design equations. The measured fractional bandwidth is 115%, with only 1 dB mid-band insertion loss at 6.4 GHz and better than -11 dB return loss across the whole passband. The measured differential-phase group delay is less than 200 ps from 2.6 to 10.1 GHz. Being a monolithic filter, it has a compact area of only 3.5 x 5.5 mm^2.**

***Index Terms* — Metalized coupled trench, bandpass filters, UWB, interdigital filter.**

I. Introduction

Ultra-wideband (UWB) has been widely investigated by academia and industry since the US Federal Communications Commission (FCC) approved the unlicensed use of the frequency spectrum from 3.1 to 10.6 GHz. UWB techniques have the advantages of a higher transmission data rate and lower power consumption. It has already been employed in applications like positioning, imaging, short-range high-data-rate communications systems and wireless personal area networks [1]. In an UWB transmitter and receiver, the UWB bandpass filter is a key subsystem, as well as a challenge to the designer. It not only requires an ultra-wide passband, to cover the target spectrum, but also maintain high selectivity to reject out-of-band signals. There have been a few reports on the realization of UWB filters using PCB and ceramic substrates, employing multiple mode resonators (MMRs) [2], hybrid microstrip/CPW [3] and cascaded high-/low-pass filters [4]. A quasi-lumped-element UWB filter using silicon micromachining was recently reported, demonstrating a compact tunable UWB notch filter [5].

Quarter-wavelength coupled microstrip lines in air have been employed for implementing high performance narrow passband filters, using relatively complicated bulk-micromachined silicon microfabrication processing [6]. However, in contrast, for wide passbands tight coupling is required, which requires extremely small gaps between coupled microstrip/CPW lines when a single metal layer is used. Moreover, the coupling coefficient becomes more sensitive as separation distances decrease [7-9]. Therefore, a challenge exists to obtain tight coupling when the coupled transmission lines employ a substrate. An alternative approach is to use multi-layers, whereby a combination of edge and broadside coupling is employed to increase the level of capacitive coupling between the lines, as demonstrated in GaAs monolithic microwave integrated circuit (MMIC) technology. Examples of this have been demonstrated in microstrip at 7.7 GHz [10], being later employed in a 10 GHz cascaded-match reflection-type phase shifter with 2-octave bandwidth [11], and in CPW within a 24 GHz MMIC serrodyne frequency translator [12].

In this paper, a coupled trench structure, fabricated by advanced silicon micromachining technology is proposed for the first time, without the need for multiple metal/dielectric layers. The structure can achieve tight coupling without extremely small separation distances, while allowing for a certain tolerance of fabrication imperfection. An interdigital UWB bandpass filter employing the coupling structure is demonstrated with excellent performance and compact size. The filter is in CPW form and, therefore, suitable for subsequent assembly or monolithic integration to make compact UWB RF front-end modules realizable.

II. Trench Coupling Structure Design and Fabrication

In order to achieve tighter coupling, a traditional 2D parallel coupled microstrip/CPW line is extended into 3D. A CPW trench structure is proposed, as shown in Fig. 1.

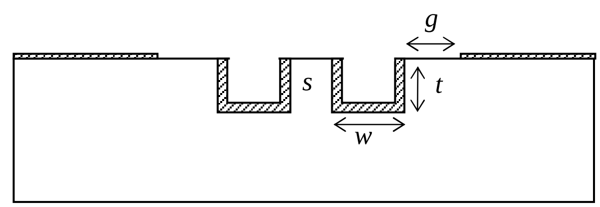


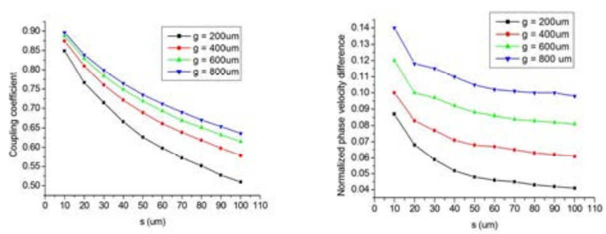
Fig.1 The schematic of an ideal CPW parallel trench

The ground plane is assumed to be infinitely wide. The two coupled trenches, with identical width *w* and depth *t*, are separated by a distance *s*. The gap distance between adjacent trench and ground plane is *g*. The high resistivity silicon (HRS) substrate has a thickness h = 525 µm and relative dielectric constant ε_r of 11.9.

Compared to conventional uniplanar CPW coupled lines, the use of the third dimension provide more flexibility in achieving the required coupling coefficient, even-odd mode impedances and phase velocity balance. By quasi-static analysis and EM simulation, the depth of the trench increases the coupling coefficient by 0.05 dB/µm, for values of *t* from 0 to ~50 µm. With t > 50 µm, the effect on coupling decreases. For example, with fixed values of w = 100 µm, g = 400 µm, t = 50 µm, -3 dB coupling can be achieved with a realizable value of s = 45 µm. Moreover, because of this relative large value of *s*, coupling is much less sensitive; being only ±0.06 dB/µm seen by HFSS™ simulations. In contrast, with conventional uniplanar CPW coupled lines, -3 dB coupling can only be achieved with s = 8 µm, and the sensitivity is ±0.2 dB/µm.

Increasing the distance between the adjacent coupled line and ground plane is another way to tighten coupling in both planar and trench forms. However, larger values of *g* will degrade the balance of phase velocity between even and odd mode, which results in a poor harmonic response close to the central frequency. This is unacceptable in UWB filter design.

The height of the trench is first determined by considering the requirements for the coupling coefficient, impedance level, balance of even-odd mode phase velocity and practical fabrication processing limitations. In this paper, for convenience, the trench width and depth are fixed at 100 µm and 50 µm, respectively. Variation of the coupling coefficient and normalized phase velocity balance, with respect to *s* and *g*, are shown in Fig. 2.



(a) Coupling coefficient

(b) Normalized phase velocity balance

Fig. 2 Effects of spatial dimension variations: (a) Coupling coefficient; and (b) Normalized phase velocity balance

The process flow to microfabricate the structure is illustrated in Fig. 3. It starts with spinning on a 4 µm thick positive photoresist (S1828) layer on a HRS (resistivity >10 kOhm.cm) wafer. The first mask, which defines the trench pattern, is then applied. After removing the UV-exposed part of the photoresist, the deep reactive-ion etching (DRIE) process removes silicon to a defined depth by controlling the etching parameters. Then a thin seed layer of chrome and copper is subsequently sputtered on the whole wafer, as well as the side wall of the trenches. Following this, a negative photoresist (Eagle 2100) is electroplated onto the wafer conformally and exposed with the second mask, which defines the planar circuit pattern. After developing, gold is electroplated onto the seed layer, where there is no photoresist. Then the remaining photoresist is removed completely and the seed layer is removed by the selective chrome and copper etchants.

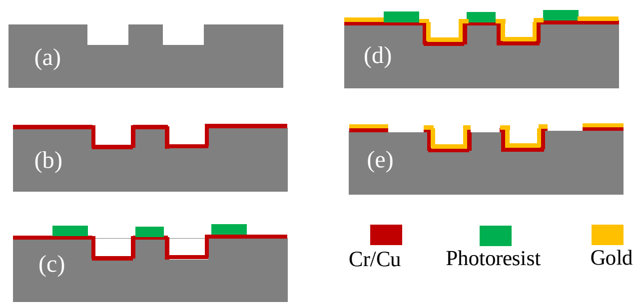


Fig.3 Process flow for metalized coupled trenches

III. Filter Design and Measured Results

The four-order UWB CPW filter structure is illustrated in Fig. 4, and designed for a 525 µm thick HRS substrate.

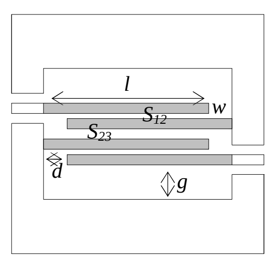


Fig.4 Illustration of proposed CPW trench coupler filter

The open circuit end of each line represents a capacitive load, with capacitance that can change by adjusting the gap distance *d*. This shortens the transmission line and pushes up the third harmonic passband away from the fundamental passband. For simplicity, this small capacitance is neglected in our synthesis process. A Chebyshev type filter having a mid-band frequency of 6.5 GHz, 110% fractional bandwidth (FBW) and passband ripple of 0.043 dB is set as the design target. The filter was synthesized using the method proposed by Abramowicz [13], which is appropriate for wideband interdigital filter design. This method transforms the ideal coupling coefficient (*k'*) suggested by Cohn [14] to real coupling coefficient (*k*) by

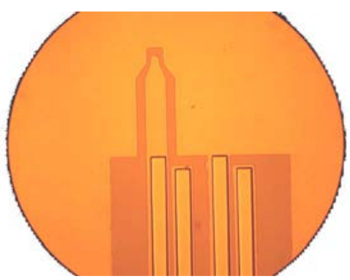
$$k = \frac{k'\sqrt{k'^2+4}}{k'^2+2}$$
$$k' = \frac{FBW}{\sqrt{g_n g_{n+1}}} \quad (1)$$

The difference between the ideal and real coupling coefficients is small for weak coupling, but becomes more significant with tighter coupling. The required coupling coefficients obtained from (1) for the first stage is k_{12} = 0.79 and the second stage is k_{23} = 0.6. By setting w = 130 µm and t = 50 µm, the values for s_{12} = 30 µm, s_{23} = 90 µm and g = 300 µm are obtained by EM simulation. Here, l = 4,100 µm represents a quarter wavelength. HFSS™ simulations and optimization have been carried out to obtain the final dimensions, given in Table I.

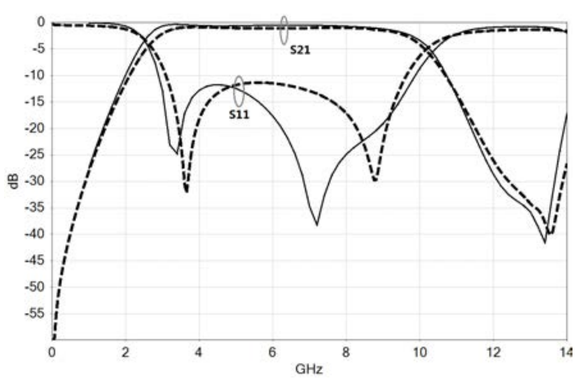
TABLE I
SUMMARY OF FILTER DIMENSIONS IN MICRONS

w	t	s_{12}	s_{23}	g	l	d
130	50	30	100	225	4,000	65

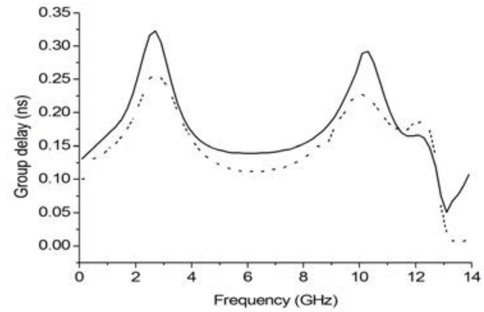
Based on the simple microfabrication process flow diagram, illustrated in Fig. 3, the filter was fabricated using just two masks. The fabricated filter is shown in Fig. 5(a), with measured and the simulated results shown in Fig. 5(b) and 5(c). It should be noted that there were no bond wires/straps or air-bridges/underpasses used in the fabrication of this filter.



(a) Microphotograph of fabricated filter



(b) Simulated (solid line) and measured (dashed line) power loss frequency responses



(c) Simulated (solid line) and measured (dashed line) differential-phase group delay frequency responses

Fig. 5 Silicon RFIC UWB filter realization

The measured 3 dB bandwidth is from 2.7 GHz to 10.1 GHz, representing a FBW of 115 %, at a center frequency of 6.4 GHz. As seen from Fig. 5, from this first prototype demonstrator design and fabrication, these results are almost exactly as predicted. The measured mid-band insertion loss of this silicon RFIC is only 1 dB, while the out-of-band suppression is -40 dB at 13.5 GHz. This filter exhibits a return loss better than -11 dB in the passband and two transmission poles are observed at 3.6 GHz and 8.8 GHz. The measured mid-band differential-phase group delay is ~110 ps, while this is kept below 200 ps across the whole passband.

IV. CONCLUSION

In this paper, the introduction, design, fabrication, measurement and application of a novel coupled trench structure has been introduced for the first time. An interdigital silicon RFIC UWB filter employing this coupling structure is demonstrated using bulk micromachining. The measured performance of this first prototype demonstrator filter is reported, showing excellent results. It is believed that this trench structure will find many applications in high-performance RFIC components and circuits.

V. ACKNOWLEDGEMENT

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