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A Novel Method for Testing Integrated RF Substrates

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***Abstract*— This paper discusses a novel and a low cost testing technique for integrated radio frequency (RF) substrates with embedded passive filters. This technique is based on resonator and regression analyses and uses low-frequency measurements to predict the filter's insertion loss at high frequency. Moreover, only one-port (S11) measurement is required for this two-port parameter prediction. Hence; this novel testing technique reduces the cost of test equipments and testing time. To show the feasibility of this proposed methodology both simulation and hardware results are presented for embedded diplexer. The results show that by our proposed methodology, testing frequency can be reduced by approximately 47% for low-pass filter and 33% for high-pass filter of the design frequency.**

I. Introduction

Recently, the advent of system-on-package (SOP) technology has motivated the embedding of several small and high performance RF passive filters in RF substrates [1-3]. Embedding of RF passive filters reduces the area of RF front-end, but increases the challenges for testing these RF embedded passive filters. Variations caused by manufacturing processes cause a shift in filter's specifications like insertion loss and band-width [4]. Unlike the surface mount RF filters, none of the internal nodes of embedded RF filters are accessible, as shown in Fig. 1. Only input/output ports 1 and 2 are accessible. Hence; there is a need to test these integrated RF substrates. The total cost to test RF substrates is mostly contributed by the equipment cost and the testing time. Costly equipments, such as high-frequency vector network analyzer (VNA) and high-frequency probes are required to test them. Moreover, the production level test time is quite high because of two-port measurements.

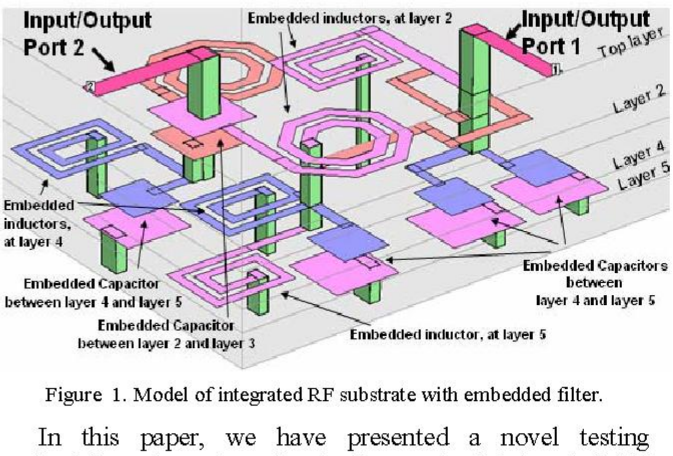

Figure 1. Model of integrated RF substrate with embedded filter.

In this paper, we have presented a novel testing methodology to reduce the testing cost of integrated RF substrate with embedded passive filters. This method requires only one-port measurement at a much lower frequency than the design frequency. Since only one port measurement is required, our proposed methodology is expected to save a considerable amount of testing time when millions of such integrated RF substrates have to be tested. Hence; this methodology reduces the cost of testing by using less-expensive probe, low-frequency VNA and reducing production level testing time.

To demonstrate, this methodology has been applied to embedded RF diplexer. Hardware measurements were also performed to show the feasibility of this methodology.

The following discussion in Section II describes our proposed test method. Section III demonstrates this methodology with the help of modeling and testing of low-pass and high-pass filters. Section IV shows the proof of concept and section V demonstrates production level test scheme for the diplexer, which is followed by the conclusions.

II. Test method

A resonator has been employed to test interconnects in multichip module (MCM) technology [5]. The method in [5] uses shift in resonance frequency of the resonator for pass or fail testing of interconnects. Our proposed testing methodology is also based on a similar principle, but it has been applied to embedded RF passive filters. Moreover, for the first time, in this paper it has been shown that insertion loss (two-port measurement) at high frequency of RF passive filter can be predicted from one-port measurement at low-frequency (please refer Fig. 2). Prediction of insertion loss at the design frequency from the low-frequency measurement is useful for large-resolution testing.

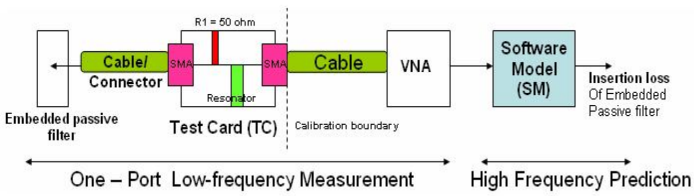

Figure 2. Setup for the proposed testing methodology.

Consider the setup shown in Fig. 2. One-port measurement of embedded RF passive filter is performed at lower frequency than the design frequency with the help of a test card (TC) and VNA.

TC consists of a coaxial resonator and a resistor of 50-ohm (R1). R1 is attached to the resonator to sense the new resonating frequency with large resolution. R1 causes S11 to approximately equal to 0 at the new resonating frequency, hence theoretically dB(S11) approaches to (-) ∞. The resonant frequency of the coaxial resonator is chosen such that it captures the variation in filter components at a much

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lower frequency than that of the operating frequency of RF filters.

Software model (SM) is made by mapping one-port measurement at low-frequency (S11) to predict insertion loss at high frequency (design frequency) using a supervised learning processing called multivariate adaptive regression splines (MARS) [6].

$$\textbf{Insertion loss}_{\textbf{high-frequency}} = \textbf{F}\ (\textbf{S11}_{\textbf{low-frequency}})$$

F (S11) is a weighted sum of basis functions made of splines, which spans S11 for the specified range of frequency at low-frequency.

III. MODELING

A. *Low-pass filter modeling*

To demonstrate this low-cost testing methodology, testing of a low-pass filter (3-dB frequency of 1.278 GHz) with a resonator (unloaded resonant frequency of 820 MHz) is shown in this section. Parasitics involved with passives are not included to simplify the explanation. Advance design system (ADS) was used for simulations.

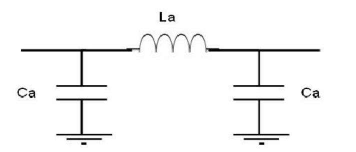

Figure 3. A prototype of low-pass filter.

In Fig. 4 shift in 3-dB frequency of the filter for variation in La and Ca is shown. Let us assume that sample C is a known golden filter (KGF) and filters B and D are marginally good. In addition to this, assume that filters A and E are bad. Hence; the aim of this testing methodology is to distinguish among these filters.

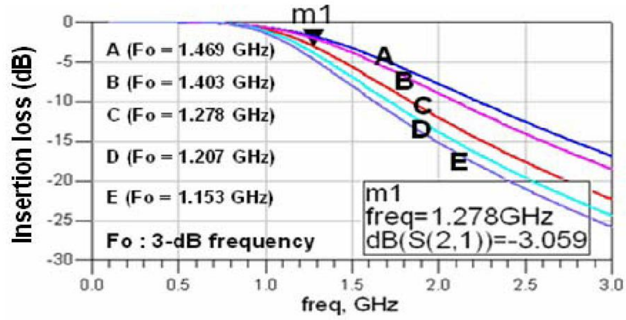

Figure 4. Insertion loss of low-pass filter for different values of La and Ca.

When these filters were simulated with TC using the setup shown in Fig. 5, correlated changes were observed in one-port S11 at low-frequency as shown in Fig. 6.

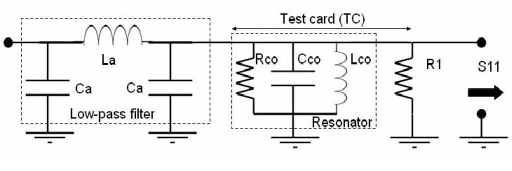

Figure 5. One-port, and low-frequency simulation using TC of passive filter.

It can be inferred from Fig. 6 that the response of filters is either towards right or left of the KGF's response. Hence; a band of frequency can be defined for initial pass-or-fail test for these filters. If a band from 655 MHz to 715 MHz is considered for good low-pass filters, filters A and E can be concluded as bad parts and filters B and D as marginally good parts.

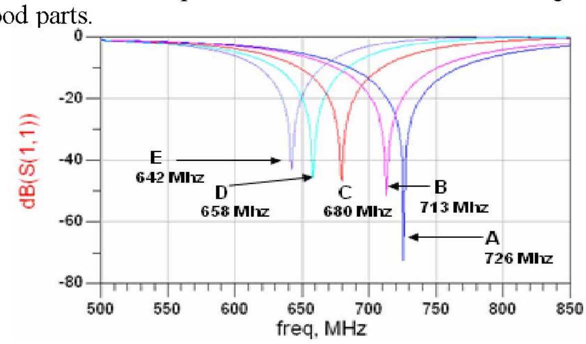

Figure 6. S11 of low-pass filter samples of test setup shown in Fig. 5.

To further demonstrate the high-resolution testing, SM was developed using 299 training samples for different values of La and Ca. SM was developed from simulated S11 of setup shown in Fig. 5. S11 parameters from 500 MHz to 648 MHz have only been used to develop SM. The predicted high-frequency insertion loss of filters B, C and D by SM in shown is Fig. 7.

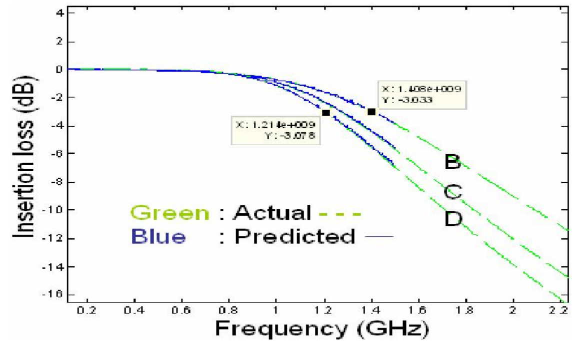

Figure 7. Predicted high-frequency insertion loss by SM of filters B, C and D.

B. *High-pass filter modeling*

To further demonstrate this novel testing methodology high-pass filter (3-dB frequency of 1.18 GHz) was modeled and tested using a resonator (unloaded resonant frequency of 585 MHz). Fig. 8 shows a prototype for high-pass filter.

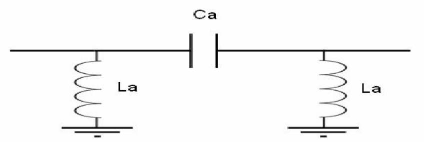

Figure 8. A prototype of high-pass filter.

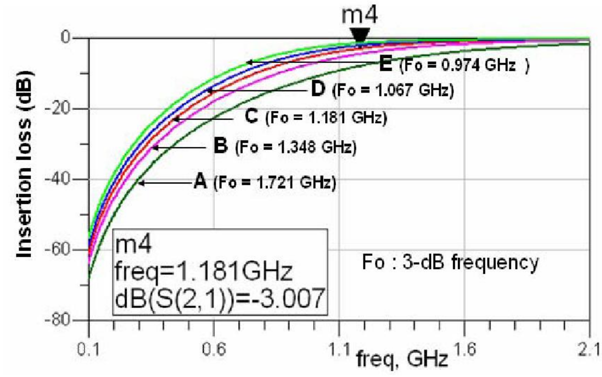

Figure 9. Insertion loss of high-pass filter for different values of La and Ca.

Insertion loss of different high-pass filters is shown in Fig. 9. As in the example above, let us assume that filters A and E are bad, filters B and D are marginally good, and filter C is KGF. One-port simulation (S11) of these filters is shown in Fig. 10. Setup shown in Fig. 5 is used for these simulations.

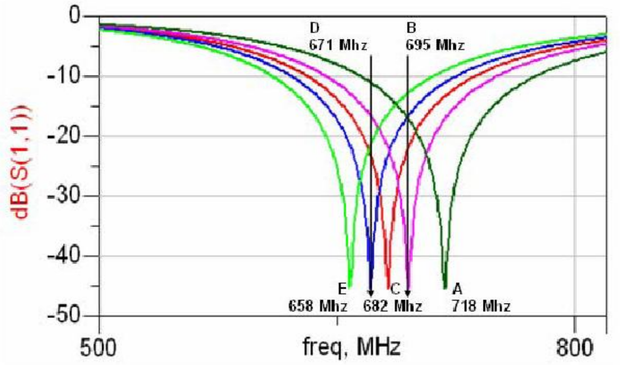

Figure 10. S11 of high-pass filter samples with test setup shown in Fig. 5.

It can be inferred from Fig. 10 that by defining a band of frequency around the response of golden high-pass filter C, filters A and E can be concluded as bad and filters B and D as marginally good high-pass filters. For high-resolution testing the predicted insertion loss of filters B, C and D is shown in Fig. 11. The SM was developed from single-port, and low-frequency simulation setup as shown in Fig.5. S11 from 600 MHz to 710 MHz of 299 high-pass filters with different values of La and Ca have been used to develop this SM.

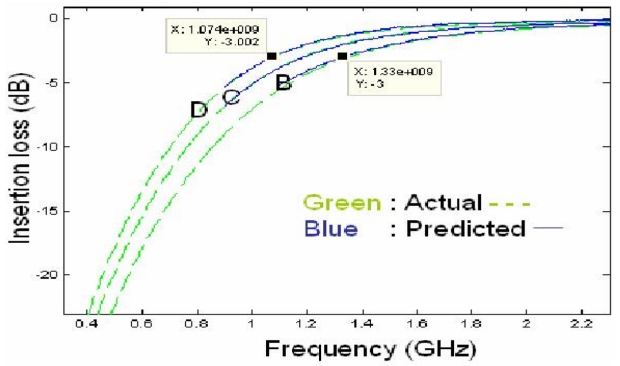

Figure 11. Predicted high-frequency insertion loss by software model (SM) of filters B, C and D.

It is important to note that the responses in Fig. 6 and Fig 10 are at a much lower frequency than the design frequency. Hence; the novel test setup shown in Fig. 2 reduces testing frequency by approximately 49% for these low-pass filters and approximately by 37% for these high-pass filters.

IV. Proof of Concept

As a proof of concept of this novel methodology, one-port hardware measurements were done as shown in Fig. 12.

The evaluation board shown in Fig. 12 consists of an integrated RF substrate with high-pass and low-pass filters embedded in it. Port 2 is common to both filters with an isolation of -45 dB. Low-pass filter is between port 1 and port 2 with a 3-dB frequency of 1.5 GHz. High-pass filter is between port 3 and port 2 with 3-dB frequency of 1.6 GHz. Four such evaluation boards were used for measurements.

TC consists of a coaxial resonator (resonance frequency of 688 MHz, TransTech # SR8800SPQ0688BYE) and R1 (50 ohm). Measurements of hardware setup for low-pass filter (Fig. 12) are shown in Fig. 13.

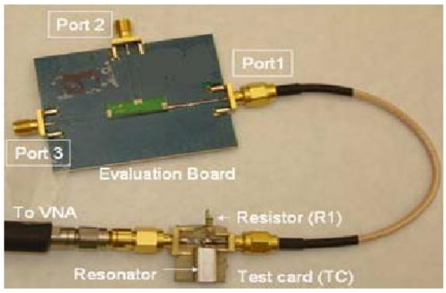

Figure 12. Hardware measurement for testing embedded low-pass filter.

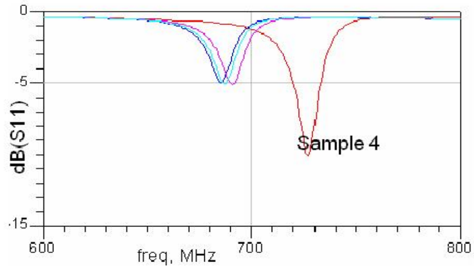

Figure 13. Measured S11 for testing low-pass filters as shown in Fig. 12.

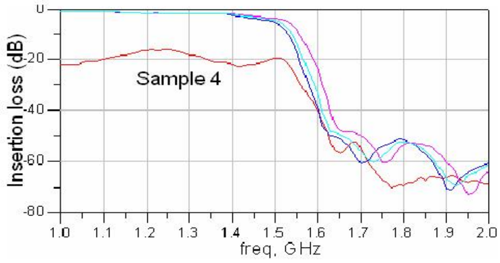

Figure 14. Insertion loss of embedded low-pass filters.

Insertion loss of these embedded low-pass filters are shown in Fig. 14. It can be inferred from Fig. 14 that sample 4 has a bad low-pass filter. According to this new testing methodology similar conclusion can be drawn from measurements shown in Fig. 13.

V. Test

In this section, the feasibility of the proposed low-cost testing methodology is shown for the production level test at wafer- level. Test card (TC) similar to section IV is directly mounted on the probe as shown in Fig 15. The integrated RF substrate shown in this figure contains 102 diplexers.

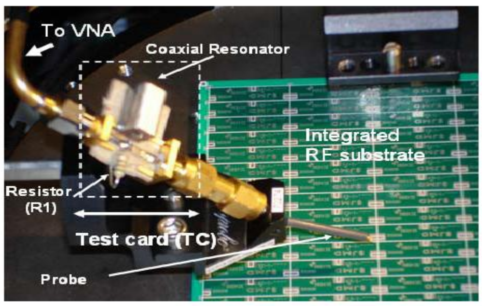

Figure 15. Wafer-level test setup using one-port methodology for 102 embedded diplexers.

One-port, and low-frequency measurement as proposed by this novel testing methodology for testing the embedded RF low-pass filter is shown in Fig. 16. Insertion loss of these filters is shown in Fig. 17.

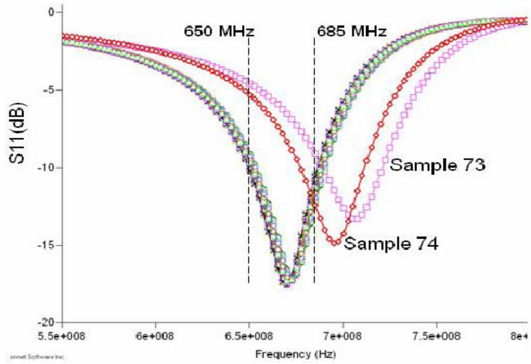

Figure 16. One-port measurement of 102 embedded low-pass filters as per setup shown in figure 15.

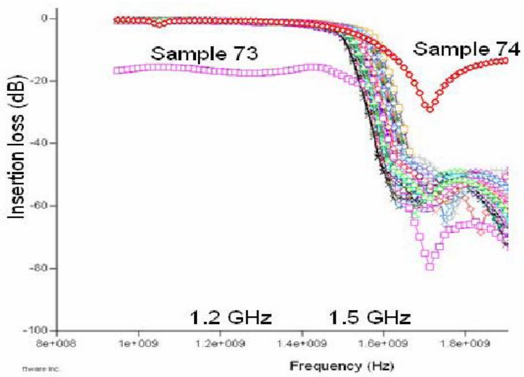

Figure 17. Insertion loss measurement of 102 embedded low-pass filters.

It can be inferred from Fig. 17 that samples 73 and 74 have bad low-pass filters, which is in agreement with the one-port, and low-frequency measurements as shown in Fig. 16. Hence; based on the setup shown in Fig. 2, a pass-or-fail decision of embedded RF low-pass filter can be made after defining a band of frequency around KGF response, like 650 MHz to 685 MHz in this case.

Fig. 18 shows one-port measurement for testing 102 embedded RF high-pass filters and Fig. 19 shows their insertion loss.

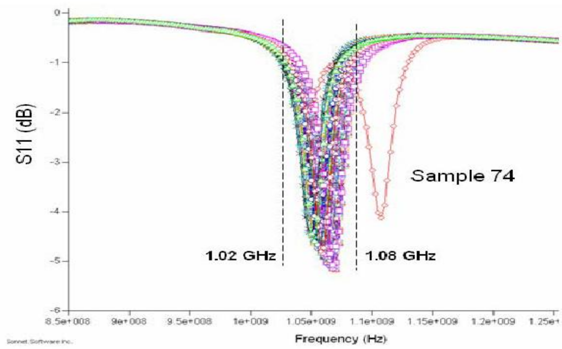

Figure 18. One-port measurement of 102 embedded high-pass filters using test card (TC).

It can be concluded from Fig. 18 that sample 74 has a bad high-pass filter. This conclusion is in agreement with insertion loss measurement of high-pass filters as shown in Fig. 19. Hence; pass-or-fail testing can be done for high-pass filters as well, by the proposed methodology.

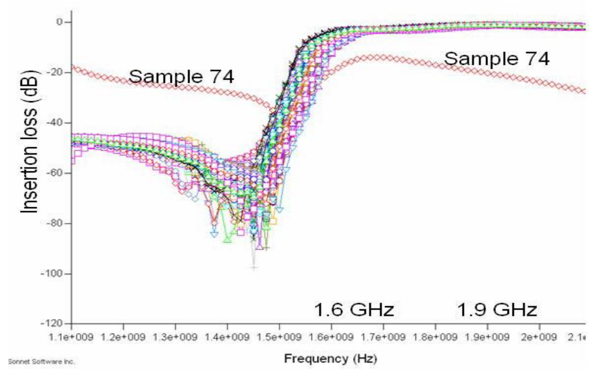

Figure 19. Insertion loss measurement of 102 embedded high-pass filters.

Moreover, high-resolution testing of this diplexer can be done by developing a software model (SM) as shown in section III. Therefore, by using this novel testing method the testing frequency is shown to be reduced by approximately 47% for low-pass filter and 33% for high-pass filter of the design frequency.

CONCLUSIONS

In this paper, we have proposed a novel testing methodology for integrated RF substrate with embedded passive filters. This method requires only one-port measurement at a much lower frequency than the design frequency of RF filters. Through simulations and hardware measurements it is shown that the testing frequency can be reduced by approximately 47% for low-pass filter and 33% for high-pass filter of the design frequency. It is also shown that one-port measurement at low frequency with test card (TC) can be used for preliminary pass-or-fail test of embedded RF passive filters. Further, we have shown that high-frequency insertion loss of these filters can be predicted from the one-port measurement at low frequency. This prediction is accomplished through a software model (SM) developed by multivariate adaptive regression splines (MARS). Such a model is useful for high-resolution testing.

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