Effects of Thin-Film Spin-On Glass Dielectric Loss on the Performance of the Uniformly Distributed RC Notch Network

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Abstract—The influence of dielectric loss on the performance of the thin-film uniformly distributed RC notch network is considered on a theoretical and experimental basis. Dielectric loss is shown to have a significant effect on the network's notch tuning frequency and the magnitude of the notch tuning resistance. An open-circuit voltage transfer function which includes a frequency-dependent dielectric loss parameter is analyzed. Double precision computed results for the first-order and higher order notch tuning frequency and notch resistance values as a function of the dielectric loss parameter are presented. The application of a proposed dielectric loss compensation technique significantly reconciles the differences between the theoretical and experimental results measured from RC notch networks fabricated with a VLSI interlevel silicon dioxide spin-on glass planarizing dielectric.

I. INTRODUCTION

MODERN microelectronic integrated circuit (IC) design continues to have a recurring requirement to realize the property of inductance. Although flat spiral inductors with micrometer-scaled dimensions and values of a few microhenries can be realized with conventional thin-film IC processing techniques, the inherent resistance of the semiconductor substrate often reduces the quality factor (Q) to a value less than unity. Alternatively, relatively complex discrete IC component designs have been utilized to simulate inductors. However, the interdependence of the actual values of the circuit parameters frequently manifest their sensitivity when reproducible performance standards are enforced in large-scale production applications [1]–[3]. Fortunately, the desirable frequency selective properties of conventionally tuned LC circuits can be realized with distributed RC notch networks that are readily fabricated with standard IC processing techniques [4], [5].

Over the past 30 a, the electrical performance of thin-film distributed RC notch networks have been thoroughly analyzed by many investigators [4]–[89]. A significant number of these investigators have studied the influence of geometrical tapering on the performance of the distributed RC struc-

ture [9], [10], [16], [20], [22], [24]–[26], [29], [32], [36], [39]–[42], [51], [57], [58], [62], [64], [77], [79], [80], [82], [86]. Additionally, voltage tunable distributed RC notch networks have been realized with thick-film, thin-film, and monolithic silicon IC processes [7]–[9], [19], [23], [30], [31], [54]–[56], [63], [66], [69], [72], [74], [80], [83], [85]. Nevertheless, because of the difficulties associated with precisely controlling the fabrication process, the tolerance values of the distributed R - and C -parameters are often unacceptable. Numerous parameters affecting the distributed RC notch network have been carefully dealt with in many experimental studies. The experimental results frequently manifest significant disagreement with the fundamental (ideal) theory developed by Kaufman [7]. The cause of these differences have been attributed to many sources, which include, load impedances [18]–[21], [29], [63], [76]; parasitic inductance [48], [63]; distributed shunt resistance [60], [69]; and dielectric loss [33], [40], [44], [60], [63], [84], [86]–[89].

In this paper, the electrical performance of uniformly distributed RC notch networks fabricated using conventional IC thin-film vacuum deposition techniques and a VLSI interlevel silicon dioxide spin-on glass (SOG) dielectric planarization material [90] is reported. Similar to the precise computations of the ideal notch tuning parameters reported by Huelsman [37], a complementary set of normalized first-order (dominant) and higher order (nondominant) tuning parameters for a uniformly distributed RC notch network with dielectric loss is reported. The proposed dielectric loss compensation technique significantly reduces the discrepancy between the experimental results and those predicted by the ideal (lossless) theory [7], [37]. These results should be of interest to those who are interested in applying this useful circuit.

II. UNIFORMLY DISTRIBUTED RC NOTCH NETWORK THEORY

The well-known ideal uniformly distributed RC notch network structure and circuit symbol are shown in Fig. 1. Fig. 2 depicts a convenient equivalent circuit model of the distributed RC structure that includes dielectric loss via the inclusion of an incremental conductance parameter [$g_s(\omega) \cdot \Delta x$] which is in series with the incremental capacitance [33], [40], [44], [60], [83]. Carson *et al.* report on an open-circuit voltage transfer function [$T(\omega)$] for the uniformly distributed RC notch network which incorporates the effect of dielectric

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Fig. 1. Uniformly distributed RC notch network structure and circuit symbol.

Fig. 2. Incremental equivalent circuit model of the uniformly distributed RC structure with dielectric loss.

loss as:

$$T(\omega) = \frac{V_o(\omega)}{V_i(\omega)} = \frac{\alpha + \xi \sinh(\xi)}{\alpha \cosh(\xi) + \xi \sinh(\xi)} \quad (1)$$

where

$$\xi = \left[\frac{src\lambda^2}{1 + sc/g_s(s)} \right]^{1/2} = \left[\frac{sRC}{1 + sRC\eta(s)} \right]^{1/2} = \left[\frac{j\delta}{1 + j\delta\eta(\omega)} \right]^{1/2},$$

$$\delta = \omega RC = 2\gamma^2 \text{ (normalized notch frequency parameter),}$$

$$\gamma = (\omega/\omega_0)^{1/2},$$

$$\eta(\omega) = [RG_s(\omega)]^{-1} = [R_s(\omega)/R] \text{ (dielectric loss parameter),}$$

$$G_s(\omega) = \int_0^\lambda g_s(\omega) \cdot dx = \lambda g_s(\omega),$$

$$R_s(\omega) = r_s(\omega)/\lambda,$$

$$R = r\lambda \text{ (distributed resistance),}$$

$$C = c\lambda \text{ (distributed capacitance),}$$

$$\alpha = R/R_n \text{ (notch resistance ratio parameter),}$$

$$\omega_0 = 2/RC \text{ (characteristic frequency parameter),}$$

$$\lambda = \text{net length of the distributed } RC \text{ structure}$$

$$s = \text{Laplace transform variable.}$$

In order for the transfer function to have a zero of transmission, the numerator of $T(\omega)$ must be zero. That is:

$$\alpha + \xi \sinh(\xi) = 0. \quad (2)$$

This complex variable expression can be separated into two real-variable equations:

$$\alpha(\delta) \cdot \tan[b(\delta)] = -b(\delta) \tanh[\alpha(\delta)] \quad (3)$$

and

$$\alpha = -\{a(\delta) \cdot \sinh[a(\delta)] \cdot \cos[b(\delta)] - b(\delta) \cdot \cosh[a(\delta)] \cdot \sin[b(\delta)]\} \quad (4)$$

where

$$a(\delta) = \left\{ \frac{1}{2} \left[\frac{\delta}{\delta^2 \eta^2(\omega) + 1} \right] \cdot \left[\delta \eta(\omega) + \{\delta^2 \eta^2(\omega) + 1\}^{1/2} \right] \right\}^{1/2}$$

$$b(\delta) = \frac{\delta}{2[\delta^2 \eta^2(\omega) + 1]} \cdot \left\{ \frac{1}{2} \left[\frac{\delta}{\delta^2 \eta^2(\omega) + 1} \right] \left[\delta \eta(\omega) + \{\delta^2 \eta^2(\omega) + 1\}^{1/2} \right] \right\}.$$

Equation (3) is a transcendental expression that is exclusively a function of the normalized notch frequency and dielectric loss parameters, and it has a solution set with an infinite number of elements, denoted by $\{\delta_n\}$. The physically practical solution set corresponds to values for n -odd (α is negative for n -even). On the other hand, (4) is a function of the notch resistance ratio, the normalized frequency, and the dielectric loss parameters. Therefore, by considering discrete values of $\eta(\omega)$, (3) can be used to calculate solutions for the normalized notch frequency parameter that yields a null. In turn, (4) yields a corresponding value of the notch resistance ratio parameter.

Solutions of (2) have been reported by several authors [33], [40], [44], [60], [63], [84]. However, there are significant discrepancies in the published results, and the differences increase in magnitude with increasing values of n (higher order (nondominant) solutions). Huelsman has addressed this issue for the ideal (lossless dielectric) case, and he has published an accurate set of results for $n = 1, 3$, and 5 [37]. Depending upon the particular application, choice of materials, and geometry of the uniformly distributed RC notch network, the higher order solutions might be advantageous.

The solutions of interest for the uniformly distributed RC notch network with dielectric loss were found using (3) and (4) along with the algorithm developed by Shampine and Allen [91] for calculating the roots of nonlinear equations. The computations were accomplished using a DEC VAX 11/780 computer and extended double precision arithmetic (33 significant digits). In those cases where a physically realistic solution exists, the results are summarized in Table I for the first-order and higher order notch tuning parameters

TABLE I
TUNING PARAMETERS FOR A UNIFORMLY DISTRIBUTED RC NOTCH NETWORK WITH DIELECTRIC LOSS

Dielectric Loss Parameter [$\eta(\omega) = R_s(\omega)/R$]	Solution Iterate [n]	Normalized Notch Frequency Parameter [$2(\omega/\omega_0)$]	Notch Resistance Ratio Parameter [$\alpha = R/R_n$]
1×10^{-6}	1	$1.118\ 681\ 613\ 922 \times 10^1$	$1.779\ 924\ 056\ 969 \times 10^1$
	3	$1.493\ 026\ 458\ 740 \times 10^2$	$3.456\ 459\ 447\ 459 \times 10^4$
	5	$4.455\ 778\ 625\ 488 \times 10^2$	$3.215\ 179\ 314\ 740 \times 10^7$
	7	$9.002\ 168\ 823\ 242 \times 10^2$	$2.478\ 421\ 210\ 191 \times 10^{10}$
	9	$1.513\ 659\ 423\ 828 \times 10^3$	$1.760\ 722\ 242\ 884 \times 10^{13}$
	11	$2.286\ 501\ 220\ 703 \times 10^3$	$1.201\ 363\ 757\ 055 \times 10^{16}$
1×10^{-5}	1	$1.118\ 837\ 253\ 571 \times 10^1$	$1.780\ 551\ 392\ 522 \times 10^1$
	3	$1.495\ 273\ 742\ 676 \times 10^2$	$3.501\ 910\ 341\ 207 \times 10^4$
	5	$4.475\ 065\ 673\ 828 \times 10^2$	$3.429\ 244\ 440\ 421 \times 10^7$
	7	$9.080\ 351\ 928\ 711 \times 10^2$	$2.975\ 429\ 493\ 178 \times 10^{10}$
	9	$1.535\ 892\ 944\ 336 \times 10^3$	$2.621\ 635\ 011\ 890 \times 10^{13}$
	11	$2.337\ 960\ 693\ 359 \times 10^3$	$3.905\ 103\ 452\ 445 \times 10^{16}$
1×10^{-4}	1	$1.120\ 397\ 872\ 925 \times 10^1$	$1.786\ 848\ 895\ 872 \times 10^1$
	3	$1.518\ 634\ 887\ 695 \times 10^2$	$4.003\ 748\ 670\ 351 \times 10^4$
	5	$4.692\ 538\ 452\ 148 \times 10^2$	$6.872\ 888\ 059\ 894 \times 10^7$
	7	$1.009\ 660\ 461\ 426 \times 10^3$	$2.572\ 398\ 770\ 692 \times 10^{11}$
	9	$1.905\ 846\ 313\ 477 \times 10^3$	$6.501\ 208\ 415\ 976 \times 10^{15}$
	11	$3.868\ 025\ 634\ 766 \times 10^3$	$9.857\ 981\ 633\ 528 \times 10^{22}$
5×10^{-4}	1	$1.127\ 443\ 218\ 231 \times 10^1$	$1.815\ 419\ 705\ 588 \times 10^1$
	3	$1.647\ 343\ 902\ 588 \times 10^2$	$7.939\ 431\ 449\ 244 \times 10^4$
	5	$7.520\ 238\ 647\ 461 \times 10^2$	$3.946\ 154\ 637\ 978 \times 10^{10}$
1×10^{-3}	1	$1.136\ 511\ 001\ 587 \times 10^1$	$1.852\ 532\ 038\ 113 \times 10^1$
	3	$1.912\ 521\ 087\ 646 \times 10^2$	$2.649\ 243\ 928\ 920 \times 10^5$
5×10^{-3}	1	$1.221\ 794\ 319\ 153 \times 10^1$	$2.220\ 782\ 218\ 770 \times 10^1$
1×10^{-2}	1	$1.379\ 062\ 393\ 188 \times 10^1$	$2.996\ 292\ 709\ 715 \times 10^1$
1.5×10^{-2}	1	$1.680\ 923\ 652\ 649 \times 10^1$	$4.874\ 677\ 780\ 074 \times 10^1$
1.845×10^{-2}	1	$2.707\ 184\ 005\ 905 \times 10^1$	$1.617\ 500\ 213\ 638 \times 10^2$

corresponding to discrete values of the dielectric loss parameter. It is noted that several authors, [33], [40], [44], have published a limited precision, small subset of the calculated results presented in Table I for the first-order ($n = 1$) solution iterate; the deviations are typically on the order of $\pm 0.4\%$.

III. EXPERIMENTAL DESIGN

In order to determine the dielectric loss characteristics of the amorphous silicon dioxide SOG thin films as a function of frequency for a specific uniformly distributed RC notch network design, an auxiliary parallel plate capacitor with the same critical dimensions as the notch network was fabricated *in situ*. Although the dielectric thin film of the *in situ* test capacitor is not exactly the same as that in the adjacent distributed RC notch network, it is assumed in the proposed compensation technique that it yields a reasonably accurate estimate of the film's dielectric loss. Table II summarizes the critical dimensions and the ideal notch tuning parameters associated with two distinct uniformly distributed RC notch network designs.

The performance of the uniformly-distributed RC notch networks was measured using a swept-frequency function generator (Hewlett-Packard, model HP 3314A, Palo Alto, CA) and a high input impedance (10 M Ω and 9 pF) digital display gain/phase detector (Hewlett-Packard, model HP 3575A) configured to directly measure the notch network's open-circuit voltage transfer function [$20 \log_{10}(V_o/V_i)$]. In order to achieve a prominent notch depth (typically greater than -60 dB), the value of the lumped notch tuning resistance parameter (α) is established via R_n with a precision

TABLE II
CRITICAL PARAMETERS OF THE UNIFORMLY DISTRIBUTED
 RC NOTCH NETWORKS

Parameter	Device Structure 1	Device Structure 2
Distributed Resistance (R)		
Film Thickness ($\text{\AA}$)	71	126
Measured Distributed Resistance ($R = r\lambda$) (Ω)	1.16×10^8	8.51×10^8
Distributed Capacitance (C)		
SOG Film Thickness ($\text{\AA}$)	1285	4783
Calculated Distributed Capacitance ($C = c\lambda$) (F)	4.9×10^{-11}	7.36×10^{-10}
Resistive Film's Electrode Gap (λ -parameter in Fig. 1)	203	508
Surface Area of the Distributed RC Structure (cm^2)	1.693×10^{-3}	9.472×10^{-2}
Calculated Characteristic Frequency Parameter ($\omega_0 = 2/RC$) (rad)	3.519×10^2	3.193

resistance (0.01- Ω resolution) decade box (Electro-Scientific Industries, Inc., model DB52, Portland, OR). An earlier publication by the author [87] describes the instrumentation arrangement used to characterize the uniformly distributed RC notch network's performance.

The relative errors (expressed as a percent) between the measured and theoretical ideal notch network tuning parameters [37] were calculated using:

$$\frac{\text{Parameter}_{\text{measured}} - \text{Parameter}_{\text{theoretical}}}{\text{Parameter}_{\text{theoretical}}} \times 100 = \Delta \text{Parameter.} \quad (5)$$

Fig. 3. Dissipation factor (loss tangent) versus frequency for the *in situ* test capacitor structures. Key: ○: arbitrary reference capacitor (1213-Å thick dielectric film), *: test capacitor for the 508-μm wide electrode gap structure; ●: test capacitor for the 203-μm wide electrode gap structure.

An impedance analyzer (Hewlett-Packard, model 4192A) was used to accomplish the dielectric loss measurements. The equivalent circuit model selected for these measurements was consistent with that of the notch network (Fig. 2). That is, the test capacitor's dielectric loss model consists of a frequency-dependent resistance [$R_s(\omega)$] in series with a capacitance (C_s). The dielectric's dissipation factor (D) (loss tangent) is given by

$$D = \omega \cdot R_s(\omega) \cdot C_s. \quad (6)$$

To determine the influence of the dielectric loss, (6) was used to generate a plot of the $R_s(\omega)$ -parameter versus frequency. A specific value of $R_s(\omega)$ corresponding to the ideal network's notch frequency was then identified. Accordingly, the ratio of $R_s(\omega)$ to R yields a reasonable first-order estimate of the dielectric loss parameter [$\eta(\omega)$]. The dielectric loss compensation scheme was then implemented by linearly interpolating between the discrete values of $\eta(\omega)$ in Table I to determine revised estimates of the lossy-dielectric uniformly-distributed RC notch network's tuning parameters. Finally, (5) was used to calculate the corresponding tuning parameter errors.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

The uniformly distributed RC notch networks were fabricated on glass microscope slide substrates. The highly conductive lower electrode (Fig. 1) was photolithographically patterned from an 8000-Å thick sputtered aluminum film (resistance less than 0.2 Ω for $f \leq 5000$ Hz). The silicon dioxide SOG dielectric thin film was applied and thermally cured consistent with the vendor's recommendations [90]. The distributed resistance film was realized by thermally evaporating a thin film of high-purity copper (99.99%) through an etched metal mask; the corresponding low-resistivity contacts were also vacuum deposited as thicker copper films. The *in situ* parallel plate test capacitors were similarly

TABLE III
TUNING PARAMETER ERRORS FOR THE IDEAL (LOSSLESS DIELECTRIC) UNIFORMLY DISTRIBUTED RC NOTCH NETWORKS

Device Structure	Tuning Parameter Errors (percent)
203-μm Wide Electrode Gap Notch Network ($n = 3$ solution iterate)	
Δf_n	11.8
ΔR_n	-8.53
$\Delta \alpha$	9.33
508-μm Wide Electrode Gap Notch Network ($n = 5$ solution iterate)	
Δf_n	7.18
ΔR_n	-14.73
$\Delta \alpha$	17.271

fabricated, except that the uppermost electrode was realized during the deposition of the RC notch network's low-resistivity copper film contacts.

Table III summarizes the tuning parameter errors associated with the two uniformly distributed RC notch network devices that were calculated with respect to the ideal (lossless dielectric) theoretical results. It is noted that the tuning parameter errors are quite substantial.

Fig. 3 depicts the dissipation factor measurements associated with the test capacitor structures. An arbitrary control test capacitor structure with a 1213-Å thick dielectric film was included in the measurements. As expected for an amorphous dielectric thin film which contains a large number of defects, there is a corresponding broad distribution of relaxation time constants which manifest themselves via the relatively constant dissipation factor measurements. The limited portion of the dissipation factor data that appears to increase with increasing frequency can be attributed to the parasitic electrode contact impedance effects. That is, although the impedance analyzer compensates for stray and residual impedance effects associated with the leads and test fixture, it

Fig. 4. Equivalent circuit series resistance $[R_s(f)]$ versus frequency for the *in situ* test capacitor structures. Key: ○: arbitrary reference capacitor (1213-Å thick dielectric film), *: test capacitor for the 508- μm wide electrode gap structure; ●: test capacitor for the 203- μm wide electrode gap structure.

cannot do the same for the notch network's contact effects. Consequently (6) can be more accurately expressed as

$$D = \omega \cdot R_s(\omega) \cdot C_s + \omega \cdot R'_s(\omega) \cdot C_s$$

where $R'_s(\omega)$ is the parasitic contact resistance. This effect is only significant for large capacitance values or very high frequencies. For example, the 508- μm wide electrode gap notch network has a measured capacitance of approximately 7.4×10^{-10} F (Table II). If $f = 6 \times 10^6$ Hz and $R'_s(\omega) = 1$ Ω , then $\omega \cdot R'_s(\omega) \cdot C_s = 0.023$, which is of the same order of magnitude as $\omega \cdot R_s(\omega) \cdot C_s$. Fortunately, the practical upper notch frequency limit (1×10^5 Hz) of the experimental distributed RC notch networks is well below the threshold where contact effects become significant.

The test capacitor's corresponding equivalent series resistance $[R_s(f)]$ was calculated from the data in Fig. 3 and (6). The low-frequency ($f \leq 6 \times 10^5$ Hz) capacitance value of the two test structures was observed to be nearly constant. (The average capacitance values were 7.36×10^{-10} F for the capacitor corresponding to the 508- μm wide electrode gap RC notch network device, and 4.9×10^{-11} F for the 203- μm wide electrode gap structure). The plot of $R_s(f)$ versus frequency is depicted in Fig. 4.

After implementing the dielectric loss compensation scheme, the tuning parameter errors were calculated using (6). The results are summarized in Table IV.

TABLE IV
DIELECTRIC LOSS COMPENSATED TUNING PARAMETER ERRORS
FOR THE UNIFORMLY DISTRIBUTED RC NOTCH NETWORKS

	203- μm Wide Electrode Gap Structure ($n = 3$ solution iterate)	508- μm Wide Electrode Gap Structure ($n = 5$ solution iterate)
Dielectric Loss Compensated		
Tuning Parameters		
$R_s(f)$ (Ω)	$3.548\,611 \times 10^3$	$2.112\,423 \times 10^4$
$\eta(f)^*$	$3.541\,528 \times 10^{-5}$	$2.518\,988 \times 10^{-5}$
$2(\omega/\omega_0)^{**}$	$1.500\,172 \times 10^2$	$4.509\,212 \times 10^2$
f_n (Hz)	$4.862\,923 \times 10^3$	$1.161\,966 \times 10^2$
R_n (Ω)	$2.780\,553 \times 10^3$	$2.170\,291 \times 10^1$
α	$3.603\,600 \times 10^4$	$3.863\,999 \times 10^7$
Compensated Tuning		
Parameter Errors (percent)		
Δf_n	9.25	5.85
ΔR_n	-4.62	3.21
$\Delta \alpha$	4.85	-3.11

*Calculated from $[R_s(f)/R]$

**Linearly interpolated from Table I

V. CONCLUSION

Comparison of the uniformly distributed RC notch network tuning parameter errors associated with the ideal (Table III) and dielectric loss compensated (Table IV) analyses suggests that the ideal (lossless dielectric) calculations are fundamentally useful for identifying approximate estimates of the notch tuning parameters (f_n and R_n). When the dielectric manifests a significant loss component in the vicinity of the intended notch frequency, the tuning parameter errors are quite large.

The potential sources that contribute to these errors are numerous, and include the effects of several idealized assumptions:

- 1) zero contact resistance;
- 2) zero stray and parasitic lead and test fixture impedances;
- 3) infinite instrumentation input impedance (for an exact open-circuit voltage measurement);
- 4) lossless dielectric,
- 5) homogeneous, defect-free thin films.

A complete identification and reconciliation of the performance effects caused by these sources is a nearly impossible task. However, dielectric losses appear to be a significant contributor to the errors involved; they are especially influential with respect to establishing the value of the lumped notch resistance parameter (R_n) which correspondingly affects the depth of the device's notch. That is, when the ideal (lossless) tuning parameter estimates are compensated for by considering the dielectric losses, the tuning parameter errors are observed to consistently decrease. In general, the notch frequency parameter (f_n) error decreases on the order of 1-2%, while the errors associated with the notch resistance parameter (R_n) are nearly halved. Additionally, the α -parameter ($= R/R_n$) error also decreases when the dielectric loss compensation scheme is implemented. Consequently, the consistent improvement in reconciling the tuning parameter errors suggests that dielectric compensation is a

valuable tool for predicting and improving the performance of uniformly distributed RC notch networks.

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