Published in final edited form as:

IEEE Sens J. 2015 October ; 15(10): 5813–5820. doi:10.1109/JSEN.2015.2449731.

Exploiting Filter Stopband for Radio Frequency Interferometer Operation

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Abstract

We propose to exploit filter stopband for high sensitivity radio frequency (RF) interferometer operation by utilizing reflection scattering parameters. Combined with passband filter operation, the modified RF interferometer effectively expands its frequency coverage. A simple model is described to analyze and predict interferometer performance. A high-pass filter and a low-pass filter are designed and built to demonstrate the interferometer operation as well as to verify the model over a frequency of 1–4 GHz. Lossy materials are shown to significantly degrade filter sensitivity enhancement effects due to reduced group delay and lower RF fields. Further work is needed to address the issue.

Keywords

Coplanar waveguide; interferometer; microwave filters; microwave sensor

I. Introduction

Highly sensitive and broadband radio-frequency (RF) sensors are of great interest for many applications in various scientific and technological areas, such as cancer cell investigation [1], molecule dynamics study [2] and electron paramagnetic resonance spectroscopy [3]. Among many technical approaches, including direct scattering parameter measurement [4] and high quality factor resonator method [5], RF interferometers have demonstrated the highest sensitivity and broadband frequency tunability with convenient system design and operation flexibility [6]. Planar transmission lines, such as coplanar waveguides (CPWs) and microstrip lines, have been used in these efforts. Yet, the high sensitivity operation often requires a large stable dynamic range, such as ~ 130 dB in [7], for minute signal detection. Thus, sophisticated detection circuits are needed and the application in rugged environment is limited.

To address this problem, filters and resonators are proposed to replace uniform transmission lines and enhance the interactions between the RF fields and material-under-test (MUT). Thus, MUT signals are boosted considerably and the required dynamic range is effectively reduced. The slowed probing wave velocity and enhanced local field intensity, when compared with that of a uniform transmission line, are responsible for the improvement [8], [9]. However, only the pass band of the filters and resonators are utilized since the use of transmission scattering parameters, S_{21} , requires significant $|S_{21}|$ values. Thus, the

achievable frequency coverage, i.e. the measuring of frequency dependent MUT information, is limited to the pass band of the filters and resonators. In this work, we propose and demonstrate that the stop band of the filters can also be exploited for high sensitivity interferometer operation, together with the use of their pass band properties.

Measuring minute property change of lossy materials at high sensitivity is another important issue since biological and chemical MUTs are often lossy. For transmission line based interferometers, losses, e.g., from DI water which is used for DNA solutions do not cause appreciable sensitivity degradation since the system can be rebalanced with attenuators [7]. For resonators, the quality factors will drop significantly due to lossy MUT [10]. Corresponding interferometer sensitivity enhancement will be reduced. For filters, lossy material effects on their dispersion and wave velocity as well as techniques to compensate loss effects are active research topics [11]. In this work, we investigate the effects of lossy material on filter performance for interferometer sensitivity enhancement.

Additionally, we design two compact CPW-based filters, one low pass (LPF) and one high pass (HPF), to study the above mentioned issues. We also provide a mathematical model to predict the sensitivity of the interferometers based on the broadband properties of the sensing elements.

This paper is arranged as the following. In section II, we describe the interferometer design and its modeling. Section III presents the design and broadband test of the filters. Section IV provides the interferometer measurement results of S_{21} in pass band and S_{11} in stop band. The measurement results verify the given model in section II. We also obtain MUT permittivity information from measurements. Section V concludes the paper.

II. The Use of Filter Stop Band and Interferometer Modeling

Fig. 1 is a schematic of the modified RF interferometer. A filter is used as the sensing element for enhanced MUT-RF interactions. An identical filter is used in the reference (REF) branch to simplify design considerations. The arrangement of the components allows the tuning of S_{21} and S_{11} separately. In stop band, a filter has large insertion loss and large reflection, i.e. $|S_{21}| \approx 0$ and $|S_{11}| \approx 1$. Destructive interference between the strong reflected waves from the two filters can be achieved at port 1 at a desired operating frequency by tuning the phase shifters along the reflected RF wave paths. The attenuators can tune $|S_{11}|$ *min* to a desired level. Thus, highly sensitive MUT detections can be achieved if strong MUT-RF interactions could be generated. However, the arrangement in Fig. 1 makes it difficult to use S_{22} since no tuning mechanisms are available for S_{22} . In a pass band, filter insertion loss is small while its return loss is large. Thus, S_{21} can be exploited for high sensitivity interferometer operation as previously reported [8], [9]. S_{12} , which is identical to S_{21} in a reciprocal system, can also be utilized. As a result, both stop band and pass band of filters help boost interferometer sensitivity for MUT sensing and cover a wider frequency range.

To generate strong MUT-RF interactions in filter stop band, RF fields at MUT location should be enhanced with extended MUT-RF interaction time τ . Nevertheless, such

information is filter specific. The dispersion relationships and field distributions in filter stop band and pass band are different, as demonstrated from full wave simulations of the designed filters in section III. Additionally, the RF probing paths for S_{11} and S_{21} are different, which will cause interferometer sensitivity and operating frequency differences. These differences could be advantageous in certain applications since they may offer spatial and frequency differentiations of MUT. Yet the basic signal propagation processes for S_{11} and S_{21} operation are the same. Therefore, only the analysis of S_{21} in filter pass band is given below and it applies to S_{11} in stop band as well.

Consider the transmission RF signal, which originates from power divider 1 (PD₁) and observed at PD₂ in Fig. 1. Over a narrow frequency range around f_0 , the transmitted signals of the REF branch and MUT branch can be approximated as

$$S_{MUT} = A_1 e^{-j\beta_1 l_1 - j\Phi_0}; \quad S_{REF} = A_2 e^{-j\beta_2 l_2 - j\Phi_0} \quad (1)$$

where A_1 and A_2 are the magnitude of transmission coefficients. The equivalent transmission lines of lengths $l_{1,2}$ and phase propagation constants $\beta_{1,2}$ are assumed for the two branches. Φ_0 is the initial phase at DC frequency for some filters. Then we can write the output $|S_{21}|$ as

$$|S_{21}(f)| = \frac{1}{2} |A_1 + A_2 e^{-j\Phi(f)}| e^{-j\Phi_0} \quad (2)$$

where Φ is the electrical length difference between the two branches; the factor 1/2 is due to power divider; Φ_0 is factored out due to the symmetrical system setup. For Φ we have

$$\Phi = \beta_1 l_1 - \beta_2 l_2 = \left(\frac{2\pi l_1}{v_{p1}} - \frac{2\pi l_2}{v_{p2}} \right) f = Cf \quad (3)$$

where $v_{p1,2}$ are the equivalent phase velocities. The coefficient C in (3) can be considered as a constant in a narrow frequency range within which dispersion can be neglected.

In general, coefficients A_1 and A_2 are frequency dependent. When the length difference, $|l_1 - l_2|$, is large, i.e. the first $|S_{11}|_{min}$ or $|S_{21}|_{min}$ occurs at low frequency, A_1 and A_2 can be assumed frequency independent since C is large and the effects of phase change with frequency will often dominate. Fig. 2 shows that such assumptions are reasonable.

When A_1 and A_2 are not strongly frequency dependent, $|S_{21}|_{min}$ occurs at frequencies where the two branches have a phase difference of

$$\Phi = (2n - 1)\pi \quad (4)$$

where $n = 1$ is considered the fundamental operating frequency of the interferometer. When MUT is introduced to the sensing area, phase and magnitude changes, i.e. Φ_F and A_F respectively, occur. The former will lead to a frequency shift, Δf , to compensate Φ_F to satisfy the relation of (3)

$$C(f + \Delta f) - \Delta\Phi_F = (2n - 1)\pi \quad (5a)$$

$$C\Delta f = \Delta\Phi_F \quad (5b)$$

The above equations can be used to obtain MUT permittivity ϵ' from measured Δf . If Φ_F is known, such as from broadband measurements, then the equations can be used to predict frequency shift Δf .

Equation (5) shows that the interferometer in Fig. 1 has higher frequency sensitivity, i.e. larger Δf for a given MUT Φ_F , when operating at its fundamental frequency. If a second interferometer also operates at the same frequency but with $n = 1$, then its coefficient C will be $(2n - 1)$ times larger. Correspondingly, the electrical length difference of the two branches in the second interferometer is $(2n - 1)$ times that of the first interferometer. Therefore, its Δf will be $(2n - 1)$ times smaller, as observed in [8].

The magnitude of $|S_{21}|_{min}$ is half of the difference between A_1 and A_2

$$|S_{21}(f_0)|_{min} = \frac{1}{2}|A_1(f_0) - A_2(f_0)| \quad (6a)$$

where f_0 is the frequency of $|S_{21}|_{min}$. Assume the MUT induced loss modifies A_1 to $A_1(1 + \alpha)$, then, (6a) becomes

$$|S_{21}(f_0)|_{min, MUT} = \frac{1}{2}|A_1(f_0) - A_2(f_0) + \alpha A_1(f_0)| \quad (6b)$$

Equation (6) shows that larger A_1 and better balance between A_1 and A_2 yield higher magnitude sensitivity, consistent with our discussions at the beginning of this section. Yet, there is an ambiguity in terms of the sign of $(A_1 - A_2)$. For example both ± 0.001 contribute to an $|S_{21}|_{min}$ of -60 dB. Thus, precautions should be taken in measurements to make sure that such ambiguity is avoided and $|S_{21}|_{min}$ can be used to obtain MUT information from measurements.

Equations (4)-(6) fail when A_1 and A_2 are strongly frequency dependent. Then, A_1 and A_2 in (1) should be written as $A_1(f)$ and $A_2(f)$. A possible source of strong frequency dependence is the sharp skirts of filters as further discussed in section IV. Another problem is reflections from the connections between the components and cables/transmission lines in

Fig. 1. As a result, certain deviations from the above analysis will happen; however, such effects are often small compared to the primary signal flow in a transmission coefficient based interferometer, for which the reflection could be incorporated into (1).

For S_{11} measurement in stop band, the above analysis is also valid except that the signal travels twice the length in the cable/transmission lines since it goes forward and reflects backward. Nevertheless, reflections between PD₁ and VNA port 1 need to be included

$$|S_{11}(f)| = \frac{1}{2} \left| A_{R1}(f) + A_{R2}(f)e^{-j\Phi(f)} + \Gamma_1 e^{-j\Phi_{\Gamma}(f)} \right| \quad (7)$$

where the reflection Γ_1 is eventually absorbed into $|S_{11}|$. If Γ_1 is very large, it is possible that low level $|S_{11}|_{min}$ cannot be achieved.

III. Design of the Filters

An LPF, Fig. 3(a), and an HPF, Fig. 3(c), are designed and fabricated to investigate the use of S_{11} , in conjunction with S_{21} , for MUT sensing. A reasonable transmission coefficient in pass band with longer group delay, τ_{db} and stronger local fields are the main filter design considerations. CPW based structure is used to build the filters since it is compact, simple and uniplanar with smooth transitions for convenient fabrication and testing. A pass band between 2 and 3 GHz is selected. The pass band together with its adjacent stop band used for $|S_{11}|_{min}$ measurement is within the operating frequency of our available circuit components. A separate straight CPW is built for sensitivity comparison. The total physical length and width, signal line and gap width of the filters and comparison CPW are the same as shown in Fig. 3.

The LPF is comprised of two back-to-back short-end CPW series stubs [12]. Its equivalent circuit in Fig. 3(b) is a simplified model originated from [12] when capacitors between the narrower signal lines and the branched arms are neglected. The element values are obtained through parameter fitting so the circuit model yields similar scattering parameters (simulated) as the corresponding filters. The HPF contains two shunt inductors (no air bridge) and a series interdigitated capacitor (IDC) with its circuit model in Fig. 3(d). It is similar to one cell of the composite right hand transmission line metamaterial [13], and it is expected to have a negative propagation coefficient. The IDC value C_1 and the shunt inductor L_2 are extracted from CAD simulations. The parasitic series inductance L_1 and the shunt capacitance C_2 are obtained from parameter fitting.

The transmission coefficients of the filters and the CPW are shown in Fig. 4(a). The results from the equivalent circuits, full wave simulations and measurements agree with each other reasonably well. The filters enable the interferometer to operate with S_{21} between 2 and 3 GHz, within which the insertion loss is reasonable. The group delay diagram, both measured and simulated, in Fig. 4(b), shows that the LPF has slow waves, mainly due to the large inductance from the reduced center conductor width. Simulation shows approximately 2 times larger $|E_{rf}|$ at MUT position in Fig. 3(a) near the cut-off frequency f_c (~3.2 GHz) compared to the field of the comparison CPW. For the HPF, it has ~4 times larger group

delay and the coupling IDC creates around 5 times larger $|E_{rf}|$ in the interdigitated gaps near f_c (~ 2.4 GHz). Therefore, the filters are expected to achieve stronger RF-MUT interactions than the CPW due to longer interaction time and stronger field intensity. Fig. 4(c) shows $|S_{11}|$ of the filters. As expected, reflections in the stop bands are strong. Their group delays, Fig. 4(d), are smaller than the delay of transmission process (i.e. S_{21}) in pass band. The field distribution in stop band of the filters shows the highest intensity at the filter and transmission line junction. Thus, we put MUT at these junction positions in S_{11} measurements. Based on the above observations, we expect S_{11} and S_{21} operations have similar sensitivities.

IV. Interferometer Operations

The obtained filters and CPW are incorporated into the system in Fig. 1 to investigate interferometer performance. A small PDMS sample ($2 \text{ mm} \times 0.5 \text{ mm} \times 0.5 \text{ mm}$) is used as dielectric MUT and placed at where $|E_{rf}|$ is the strongest, such as the locations indicated in Fig. 3.

A. Sensitivity Enhancement Test: Measuring S_{21}

For convenience, we choose Φ so that the 8th to 10th minima of CPW and LPF based interferometers lie between 2 and 3 GHz, as shown in Fig. 5(a). Only one CPW and one LPF are used in MUT branch of Fig. 1 for CPW and LPF measurements. For HPF, the minima numbers are difficult to recognize due to large insertion loss at low frequencies. One HPF is used in each branch to cancel out the non-zero phase at DC for simplicity in analysis. At each harmonic, R_1 and R_2 in Fig. 1 are tuned to achieve an $|S_{21}|_{min}$ of -60 dB, as shown by the solid lines in Fig. 5(b) for the 8th minima. The system is stable and reliable for investigation at the level of -60 dB. The MUT is then introduced to shift the curves to the dashed lines in Fig. 5(b). Fig. 5(c) and (d) show the measured $|S_{21}|_{min}$ and f at three frequencies. It is shown that the HPF enables the highest sensitivity in both $|S_{21}|_{min}$ and f followed by LPF. The f trend agrees with the group delay qualitatively. The $|S_{21}|_{min}$ of filters are much larger than that of CPW due to stronger interactions between the PDMS slab and RF fields despite their higher insertion loss.

The dashed lines in Fig. 5(c) and (d) are calculated results with the equations described in section II. Broadband measurement results of the filters and comparison CPW are used for calculation. The calculated results are also validated by simulations at frequencies around the symbols by importing broadband filter measurement results, with and without MUT, into a circuit model of the interferometer in Fig. 1. The predictions of measured sensitivity from calculation are reasonable even though the measured results are significantly lower. A possible reason for the discrepancy is that the frequency dependent properties of actual circuit components are not considered in calculation and simulations.

To obtain the permittivity from the measured scattering parameters of a given MUT at a given MUT location, we use (3)-(5). First, Φ_F which is the phase change of the interferometer caused by MUT, is obtained with (5) and the measured f in Fig. 5(d). The magnitude information is not used here since the components in the system shows magnitude variation as frequency shifts. Then, parametric simulations in HFSS are

conducted for the comparison CPW and filters to provide a relationship between Φ_F and the permittivity of the MUT. Compare the results from the two steps, MUT permittivity is obtained, similar to the process in [14]. The calculated results are shown in Table I at the 3 different measurement frequencies in Fig. 5(d), labeled as 1, 2 and 3, from low to high.

The calculated ϵ_r ranges between 2 and 3, which is the often reported permittivity of PDMS. The HPF and the two higher frequency points of LPF give smaller permittivity values since the measured results are smaller than the calculated ones as shown in Fig. 5(d). The deviation is believed to be caused in part by the uncertainty of MUT locations in Fig. 3.

1) Fundamental Mode Operation: Higher Sensitivity: We modified the branch length of the interferometer to satisfy $n = 1$ at 2.35, 2.65 and 2.95 GHz respectively for the filter and CPW based system operation. The filters and CPW are the same as in previous experiments. Fig. 6 shows that the filters yield larger f and $|S_{21}|_{\min}$ than those in Figs. 5(c) and (d), which also agree reasonably well with the calculated results from (5). It shows that fundamental frequency operation produces close to $(2n - 1)$ times larger f . The $|S_{21}|_{\min}$ parameter is larger than the results in Fig. 5 since the frequency dependent transmission coefficient contribute to a larger amplitude change.

When an HPF is used in MUT branch while a CPW is used in REF branch, the results around 2.96 GHz are shown in Fig. 7. Smaller HPF f is obtained compared with the results in Fig. 6(b). There are a few possible reasons for the observed lower sensitivity. First, the HPF induces additional phase delay, i.e. Φ_0 in (1), compared with CPWs. The delay makes the equivalent branch length longer. As a result, the interferometer may be working at higher harmonics mode at the targeted frequency. Another reason is that the frequency dependent A_1 ignored in section II makes the interferometer work with a different mechanism. For ease of analysis, we assume that A_2 and Φ are frequency independent and $\Phi = \pi + \delta\varphi$ when MUT is introduced. It can be shown that $|S_{21}|_{\min}$ happens at $A_1 = A_2 \cos \Phi$ and $|S_{21}|_{\min} = |A_1 \sin \delta\varphi|$. In this case, $\delta\varphi$ causes $|S_{21}|_{\min}$ to shift vertically other than horizontally, as shown in Fig. 7.

2) Lossy Materials: Dielectric measurements are often carried out with the presence of lossy material, such as DNAs in lossy buffer solutions [7]. The lossy buffer may alter the dispersion relationship of the filters and reduce their sensitivity enhancement effects. To investigate lossy material effects, an absorbing material of 3 mm $\times$ 3 mm $\times$ 9.5 mm (MT-30, Cumming Microwave) is placed on the sensing structure surface along the signal line direction, as indicated by the dashed rectangle in Fig. 3. It covers the two CPW gaps of the CPW. Figs. 8 (a) and (b) show the measured broadband transmission coefficients and the delay of the filters before and after introducing the lossy material. For the HPF, the transmission coefficient almost stays the same except that the permittivity of the lossy material shifts the curve left. The electrical field intensity decreases after the lossy material is introduced on filters and CPW. The engineered delay of the filters is also deteriorated when loss is introduced. Thus, loss of sensitivity for filters based interferometers is expected.

The interferometers are then tuned to -60 dB with the lossy material on the filters and the CPW. The dielectric MUT is still placed where the electrical field is the strongest as in the measurements for sensitivity analysis above. The results are summarized in Figs. 8 (c) and (d). It is observed that filter based interferometers experience more than twice f degradation while CPW based interferometer has minimum degradation for both $|S_{21}|_{min}$ and f . The degeneration of f qualitatively agree with the reduction of group delay. For $|S_{21}|_{min}$, filter based interferometers decrease by half and CPW based interferometer retains similar values. The calculated MUT permittivity value ϵ' from each f are listed in Table II, which do not agree with the results in Table I very well even though they are usually within the expectations. Further work is needed to obtain repeatable and accurate MUT dielectric properties including ϵ'' .

Loss effect on resonator is also evaluated with the resonator designed in [9]. Simulation and measurement results show that loss has similar effects on resonator and filters. Nevertheless, filters and resonators can still enhance interferometer sensitivity significantly when compared to CPWs.

B. Sensitivity Enhancement Test: Measuring S_{11}

The setup in Fig. 1 allows the tuning of S_{11} in stop band of the filters. Fig. 9(a) is the broadband performance of the interferometer between 2 and 4 GHz with an LPF in each branch. Fig. 9(b) is a zoom in view at ~ 2.55 GHz after tuning both S_{11} and S_{21} to ~ -60 dB. The S parameter starting levels, i.e. $|S_{11,0}|$ and $|S_{21,0}|$ in Fig. 1, of the interferometer follow the broadband $|S_{11}|$ and $|S_{21}|$ trend of LPF, respectively.

Both S_{11} and S_{21} can be tuned simultaneously at the same frequency point or different frequency points, such as Figs. 9(b) and (c). However, for high sensitivity operation, it is much easier to tune S_{11} and S_{21} separately, using one at a time. Therefore, in measurements below, we only tune S_{11} in stop band with the same interferometer setup used for Fig. 5. A filter is used in each branch to provide sufficient reflection for proper operation.

The results of $|S_{11}|_{min}$ and f are summarized in Figs. 9(d), (e). It is shown that $|S_{11}|_{min}$ is on the same order with $|S_{21}|_{min}$, but f is only half the values of S_{21} measurements. This is reasonable since the reflection wave travel distance doubles, and the frequency sensitivity is degraded according to previous analysis. These results show that the use of S_{11} effectively expands the working frequency to stop band and is promising for high sensitivity measurement due to the strong field intensity.

The use of S_{11} is also attempted with CPW based interferometers. But the obtained results do not show reliable and repeatable trend. Much weaker reflections, since there is no stop band, could be the main reason.

V. Discussions and Conclusion

Quadrature hybrids have been used to replace power dividers to obtain S_{11} information at the same operating frequency in [15]. No tuning was considered to achieve high sensitivity

S_{11} operation. When such hybrids are used in Fig. 1 to replace the power dividers, the reflection signals can also appear at the input port of the left hybrid.

In summary, the interferometer architecture is modified to allow the tuning of S_{11} . Thus, the working frequency bandwidth is expanded to include the stop band. It is shown that the interferometer has similar sensitivity in stop band and in pass band. Thus, simple six-port circuit reflectometers could be exploited to build on chip interferometer system with the circuit in Fig. 1 [16]. Furthermore, the proposed model predicts the sensitivity of the interferometer reasonably well. Nevertheless, lossy materials degrade sensitivity enhancement effects of filters and resonators due to reduced group delay. Further work is needed to overcome this issue.

Acknowledgments

The work was supported in part by the National Institutes of Health under Grant 1K25GM100480-01A1 and in part by the Division of Chemistry through the National Science Foundation under Grant CHE-1152892. The associate editor coordinating the review of this paper and approving it for publication was Dr. Richard T. Kouzes.

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Fig. 1.

A schematic of the modified RF interferometer with a filter as sensing structure. For a transmission line based setup, the filters are replaced with planar transmission lines, such as CPWs.

Fig. 2.

The measured magnitude versus frequency (solid lines) of filters and a comparison CPW as well as corresponding phase differences $\Phi(f)$ (dashed line) around an interferometer operation frequency point. The filters and CPW will be further discussed in Section III. The phase difference, $\Phi(f)$, is shifted to 0 degree at 2.5 GHz. Only one typical $\Phi(f)$ is shown since all $\Phi(f)$ are similar.

Fig. 3.

(a) A layout of the LPF with $L_f = 19$ mm and $W_f = G_f = 0.4$ mm. (b) An equivalent circuit model of the LPF: $L_1 = 4.46$ nH, $L_2 = 0.06$ nH, $C_1 = 1.31$ pF. (c) A layout of the HPF with $L_c = 11.4$ mm, $G_c = 0.2$ mm, $W_c = 0.36$ mm, $L_l = 5.6$ mm, $G_l = 0.64$ mm, and $W_l = 0.25$ mm. (d) An equivalent circuit model of the HPF with $L_1 = 1.1$ nH, $C_1 = 0.9$ pF, $L_2 = 1.65$ nH, $C_2 = 0.7$ pF.

Fig. 4.

(a) The $|S_{21}|$ of the CPW and the filters in pass band. The flat curves are for CPW. (b) Measured (solid line) and simulated (dashed line) transmission delay of the CPW, LPF and HPF in pass band. The discrepancy between measurement and simulation results of the HPF around 2.9 GHz is due to reduced $|S_{21}|$ in (a). (c) The $|S_{11}|$ of the filters in stop band. (d) The reflection delay of the filters in stop band.

Fig. 5. Measurement results at harmonic frequencies. (a) Broadband interferometer operation. (b) A zoom-in view of the 8th minima (The CPW and HPF plots have been shifted 36.3 and 153.4 MHz higher, respectively, relative to their original value in (a) for clearer comparison. (c) Measured and calculated $|S_{21}|_{min}$, and (d) f of the interferometers.

Fig. 6. (a) Measured and calculated sensitivity of the interferometers at $n = 1$: (a) $|S_{21}|_{\min}$ and (b) f .

Fig. 7.
Measurement results of $|S_{21}|_{min}$ when f_0 is ~ 2.95 GHz.

Fig. 8.

(a) The $|S_{21}|$ of the CPW and the filters with and without lossy material. The flat curves are for CPW. (b) The delay of the CPW and the filters with (solid lines) and without lossy material (dashed lines). (c) Measured and calculated $|S_{21}|_{min}$, and (d) Δf of the interferometer with lossy material.

Fig. 9.

(a) Broadband interferometer operation with LPF measuring S_{11} and S_{21} at the same time. (b) and (c) A zoom-in view at ~2.55 GHz measuring S_{11} and S_{21} at the same time. (d) Measured $|S_{11}|_{min}$ and (e) f of S_{11} .

TABLE I

Calculated MUT Permittivity

Sensor Type	1	2	3
CPW	3.0921	2.8600	2.1223
LPF	3.0494	2.4137	1.9445
HPF	2.4884	2.3195	2.4582

TABLE II

Calculated MUT Permittivity

Sensor Type	1	2	3
CPW	2.5029	2.7460	3.0336
LPF	2.4157	2.6680	2.5721
HPF	2.7063	2.4053	3.0350