$$d_{31} = (596.3251 + 188.1409f - 1741.4770f^2 + 465.6756f^3) \times 10^{-6} \tag{A3n}$$

$$d_{32} = (124.9655 + 577.5381f + 1366.4530f^2 - 481.1300f^3) \times 10^{-7} \tag{A3o}$$

$$d_{33} = (-530.2099 - 2666.3520f - 3220.0960f^2 + 1324.4990f^3) \times 10^{-9}. \tag{A3p}$$

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# A Study of Measurements of Connector Repeatability Using Highly Reflecting Loads

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***Abstract*—This paper investigates the repeatability of measurements of the reflection coefficient $\Gamma$ of highly reflecting devices with changes in the RF connector joint. The changes in the connector joint are due to disconnecting and reconnecting the connector pair. It is shown that many of the measurement discrepancies observed in practice can be explained with a simple connector model. The paper shows that the sensitivity of measuring RF connector changes can be increased by using highly reflecting loads. The changes in $\Gamma$ due to changes in resistance or reactance can be four times greater for highly reflecting devices ($|\Gamma| \approx 1$) than for nonreflecting devices ($|\Gamma| \approx 0$). Experiments on two devices with 14-mm connectors are described in order to compare them with theory. The basic principles described in this paper should be beneficial to connector designers who need to observe small changes in connector parameters and to the work of calibration standards designers, where small connector imperfections are a major part of their measurement uncertainty.**

## I. Introduction

It has been recognized for some time that coaxial connectors limit the accuracy of many of the measurements at microwave frequencies. It is difficult to make measurements with today's modern network analyzer and not be acutely aware of connectors and their lack of repeatability. Recent studies at the National Bureau of Standards have been successful in developing an improved connector model and in developing a technique for measuring parameters for that model [1]. This paper examines the implications of that model on the measurements of the reflection coefficient $\Gamma$ of highly reflecting devices ($|\Gamma| \approx 1$). In particular, this paper investigates the repeatability of measurements of $\Gamma$ with changes in the RF connector joint parameters. The changes in $\Gamma$ due to changes in resistance, or reactance at the connector's center conductor joint, are described. It is shown that the changes in $\Gamma$ can be up to four times greater for highly reflecting devices than for the nonreflecting case ($|\Gamma| \approx 0$). The changes in $\Gamma$ are frequency dependent and are greatest at or near the maximum current ($\arg(\Gamma) = 180°$) or the current null ($\arg(\Gamma) = 0°$) frequencies. The basic principles described in this paper should be beneficial to connector designers who need to observe small changes in connectors and in the design of calibration standards, where connector imperfections are a major part of the measurement uncertainty.

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## II. Theory

Consider the circuit shown in Fig. 1, composed of a connector with joint scattering parameters $S_{ij}$, a coaxial transmission line of length $l$, and a termination $\Gamma_T$. This connector joint model and methods for determining $S_{ij}$ are described in a paper by Daywitt [1]. The reflection coefficient $\Gamma$ looking into this combination is given by

$$\Gamma = S_{11} + \frac{S_{12}^2 \Gamma_l}{1 - S_{22}\Gamma_l} \tag{1}$$

where $\Gamma_l$ is the reflection coefficient looking into the transmission line. The scattering parameters for the connector joint are given in [1] as

$$S_{11} = S_{22} = \frac{r}{2} + \frac{x}{2} - y \tag{2}$$

$$S_{12} = S_{21} = 1 - \frac{r}{2} - \frac{x}{2} - y \tag{3}$$

where $r$ is the normalized joint resistance:

$$r = R/Z_0 \tag{4}$$

$x$ is the normalized joint reactance:

$$x = j\frac{2\pi fL}{Z_0} \tag{5}$$

and $y$ is the normalized joint admittance:

$$y = j2\pi fCZ_0. \tag{6}$$

The joint's length is assumed to be small relative to a wavelength. Substituting (2) and (3) into (1) and eliminating second-order terms in $r$, $x$, and $y$ results in

$$\Gamma = \Gamma_l + (1-\Gamma_l)^2\frac{r}{2} + (1-\Gamma_l)^2\frac{x}{2} - (1+\Gamma_l)^2 y. \tag{7}$$

Therefore, the change in $\Gamma$ due to changes in $r$, $x$, or $y$ is given by

$$\frac{\partial \Gamma}{\partial r} = \frac{(1-\Gamma_l)^2}{2} \tag{8}$$

$$\frac{\partial \Gamma}{\partial x} = \frac{(1-\Gamma_l)^2}{2} \tag{9}$$

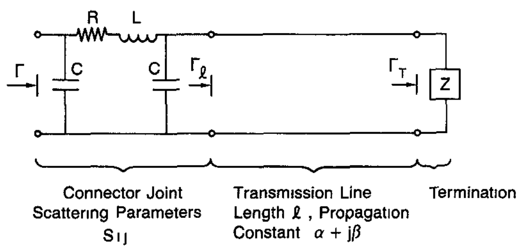


Fig. 1. Circuit model of connector joint, transmission line, and termination.

and

$$\frac{\partial \Gamma}{\partial y} = -(1+\Gamma_l)^2 \tag{10}$$

respectively.

First, assume that $\Gamma_l$ is an idealized highly reflecting termination with a reflection coefficient of

$$\Gamma_l = e^{-jkf}. \tag{11}$$

At the frequencies where $kf = \pi$, $3\pi$, etc. (current maxima),

$$\frac{\partial \Gamma}{\partial r} = \frac{\partial \Gamma}{\partial x} = 2 \tag{12}$$

while

$$\frac{\partial \Gamma}{\partial y} = 0. \tag{13}$$

However, at the current minima, where $kf = 2\pi$, $4\pi$, etc.,

$$\frac{\partial \Gamma}{\partial r} = \frac{\partial \Gamma}{\partial x} = 0 \tag{14}$$

while

$$\frac{\partial \Gamma}{\partial y} = -4. \tag{15}$$

Next, consider the case where $\Gamma_l$ is an idealized nonreflecting termination with $\Gamma_l = 0$. Now one sees that

$$\frac{\partial \Gamma}{\partial r} = \frac{\partial \Gamma}{\partial x} = \frac{1}{2} \tag{16}$$

and

$$\frac{\partial \Gamma}{\partial y} = -1. \tag{17}$$

Thus, the sensitivity of $\Gamma$ to changes in $r$, $x$, and $y$ can be up to four times greater for the highly reflecting case (at the current maxima or minima) than for the nonreflecting case. This observation can be particularly useful if one is trying to measure or characterize the repeatability of connectors. It can also be useful in some standards measurements where connector repeatability, or lack thereof, is a prime consideration.

Equation (7) can be further simplified for the highly reflecting case [1]. Assume that

$$\Gamma_l = e^{-2(\alpha l + j\beta l)}\Gamma_T \tag{18}$$

where $\gamma = \alpha + j\beta$ is the propagation constant of the transmission line shown in Fig. 1, and

$$\Gamma_T = e^{-j\phi} \tag{19}$$

is the reflection coefficient of the highly reflecting termination. The reflection coefficient $\Gamma$, neglecting second-order terms in $\gamma$, $r$, $x$, and $y$, is approximately given by

$$|\Gamma| = 1 - 2\alpha l - r[1-\cos(2\beta l - \phi)] \tag{20}$$

and

$$\arg(\Gamma) = -2\beta l + \phi - |x|[1-\cos(2\beta l - \phi)] - 2|y|[1+\cos(2\beta l - \phi)]. \tag{21}$$

This case is examined in more detail in the measurements.

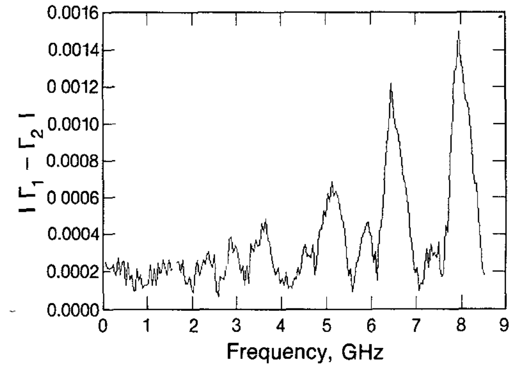


Fig 2 Measurements of $|\Gamma_1 - \Gamma_2|$ versus frequency for two connections of a 10-cm air transmission line terminated in an open circuit.

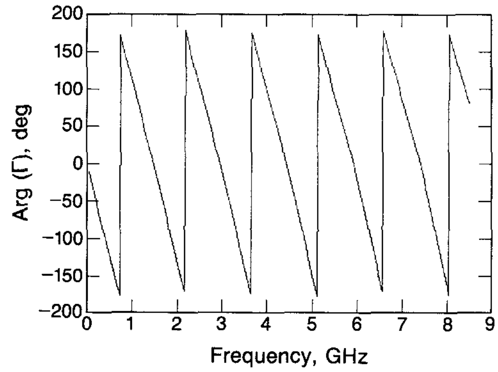


Fig. 3 Measurements of $\arg(\Gamma_1)$ versus frequency for a 10-cm air transmission line terminated in an open circuit

## III. Measurements

Many of the connector repeatability measurements that are observed in actual practice can be explained with the simple model described. For example, consider the following measurements of $\Gamma$ looking into a 10-cm air-dielectric transmission line which is terminated in an open circuit. The air line is beadless except at the open end, which is supported by a boron-nitride bead. The joint under test is a commercially available, 14-mm precision connector pair. Only one of the center conductors has a "flower" spring center contact. The center conductor on the air line is "flowerless," which is typical of beadless air lines. Fig. 2 shows measurements of $|\Gamma_1 - \Gamma_2|$ where the device is disconnected and reconnected (random orientation) between the two measurements of $\Gamma$. If Fig. 2 is compared with Fig. 3, one sees that significantly more change occurs at the high-current ($\arg(\Gamma) = \pm 180°$) frequencies than at the low-current ($\arg(\Gamma) = 0°$) frequencies. This is also seen in Figs. 4 and 5, which show $|\Gamma_1| - |\Gamma_2|$ and $\arg(\Gamma_1) - \arg(\Gamma_2)$, respectively. Note that the changes in $\Gamma$, due to the disconnecting and reconnecting of the device, primarily occur at the current maxima.

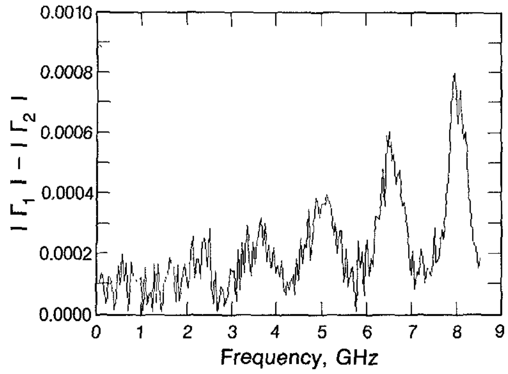


Fig 4 Measurements of $|\Gamma_1|-|\Gamma_2|$ versus frequency for two connections of a 10-cm air transmission line terminated in an open circuit.

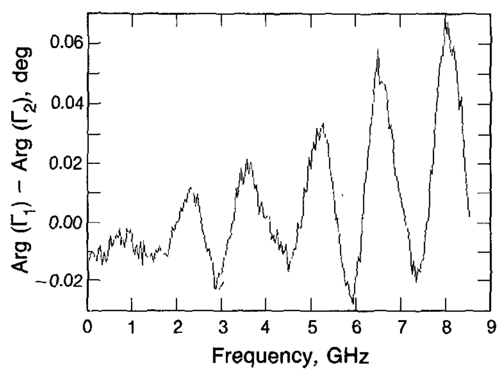


Fig. 5. Measurements of $\arg(\Gamma_1)-\arg(\Gamma_2)$ versus frequency for two connections of a 10-cm air transmission line terminated in an open circuit.

From (20), it can be shown that

$$|\Gamma_1|-|\Gamma_2|=(r_2-r_1)(1-\cos(2\beta l-\phi)) \tag{22}$$

where $r_1$ and $r_2$ are the normalized joint resistances from the first and second connect of the device. At the current maxima,

$$(r_2-r_1)=\frac{|\Gamma_1|-|\Gamma_2|}{2}. \tag{23}$$

Similarly, from (21),

$$\arg(\Gamma_1)-\arg(\Gamma_2)=(|x_2|-|x_1|)(1-\cos(2\beta l-\phi)) + 2(|y_2|-|y_1|)(1+\cos(2\beta l-\phi)) \tag{24}$$

which means that at the current maxima,

$$(|x_2|-|x_1|)=\frac{\arg(\Gamma_2)-\arg(\Gamma_1)}{2}. \tag{25}$$

Using Fig. 4 and (23), the change in normalized joint resistance between the two connects is estimated to be

$$(r_2-r_1)\cong 0.00003 f_{\mathrm{GHz}}^{1.25}. \tag{26}$$

The phase change shown in Fig. 5 is probably due to a change in the inductance since the changes occur at the current maxima $((2\beta l-\phi)=\pi, 3\pi$, etc). The change in normalized reactance between the two connects is estimated, using Fig. 5 and (25), to be

$$(|x_2|-|x_1|)=0.000075\, f_{\mathrm{GHz}}$$

which means that

$$\frac{(L_2-L_1)}{Z_0}=0.012\times10^{-12}\ \mathrm{H}/\Omega. \tag{27}$$

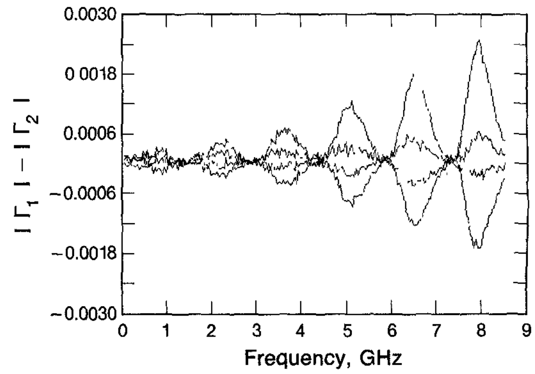


Fig. 6. Measurements of $|\Gamma_1|-|\Gamma_2|$ for eight different connections of a 10-cm air transmission line terminated in an open circuit.

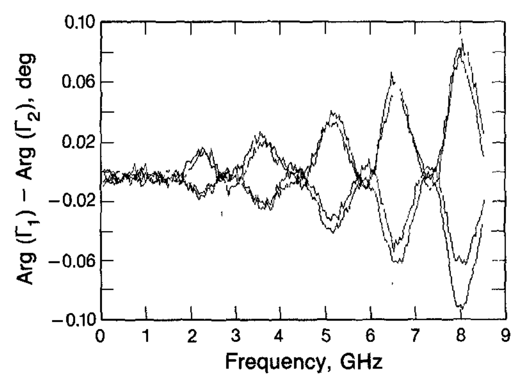


Fig. 7. Measurements of $\arg(\Gamma_1)-\arg(\Gamma_2)$ for eight different connections of a 10-cm air transmission line terminated in an open circuit.

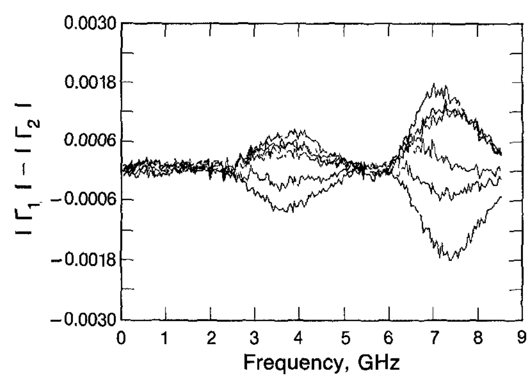


Fig. 8. Measurements of $|\Gamma_1|-|\Gamma_2|$ versus frequency for multiple connections of a 4-cm air transmission line terminated in a short circuit

The changes shown in Figs. 4 and 5 are typical of what is normally observed for that device. Figs. 6 and 7 show examples of changes that were observed during other connects and reconnects of the device. As can be seen, the changes in $\Gamma$ primarily occur at the current maxima, with the measurements of $\Gamma$ fairly repeatable at the current minima.

These measurements are also typical of what is observed on similar devices with 14-mm connectors. For example, Fig. 8 shows measurements of $|\Gamma_1|-|\Gamma_2|$ for a 4-cm air line terminated in a short circuit (4-cm offset short). Both center conductors in this 14-mm joint contain "flower" spring contacts. There are no dielectric supports in this particular device. The current minima for this device occur at 1.9 and 5.6 GHz, while the current maxima occur at 3.8 and 7.5 GHz. Note that the change is

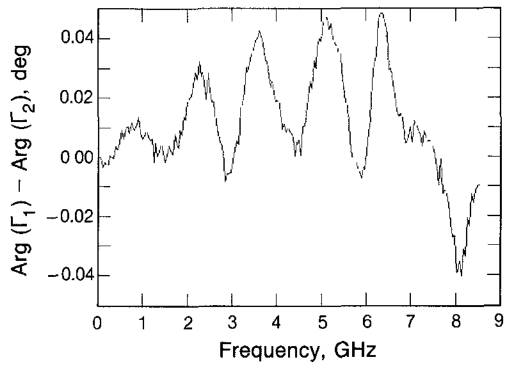


Fig 9. Measurements of $\arg(\Gamma_1)-\arg(\Gamma_2)$ versus frequency for two connections of a 10-cm air transmission line terminated in an open circuit.

predominantly at the current maxima. The measurements of $\arg(\Gamma_1)-\arg(\Gamma_2)$ are similar to those shown previously in that the changes occur at the current maxima.

## IV. Discussion

It should be emphasized that the purpose of this paper is to show that some of the measurement discrepancies observed because of connectors can be explained with a simple connector joint model. It is not meant to be an exhaustive study of connector joints. Much work remains to be done in both understanding and modeling connector joints. The intent of this paper is to document some of the current observations.

Much of the work to date reaffirms the complexity of the connector joint. Ideally, one would expect the resistive component to vary with frequency as $f^{1/2}$. However, as noted by Daywitt [1], variation of up to $f^{2.8}$ has been observed. The inductive term can also exhibit a complex behavior as a function of frequency. Fig. 9 shows one example of this complexity. Plotted here is $\arg(\Gamma_1)-\arg(\Gamma_2)$ for the 10-cm air transmission line terminated in an open circuit. Note that the sign of the phase change is negative at 8 GHz and positive at the lower frequencies. This type of behavior is not explainable with the simple model shown.

Also, it is not known what effect the network analyzer calibration errors have. Network analyzers, to some degree, can transform phase information into magnitude and magnitude into phase information. The extent to which this is happening is beyond the scope of this study. Numerous network analyzer calibrations were used in collecting the data for this report.

## V. Conclusions

The simple connector joint model described in this paper appears to be a valuable tool in understanding the changes that occur at connector joints. Theory predicts that the changes in $\Gamma$ due to changes in resistance or reactance can be up to four times greater for highly reflecting devices than for nonreflecting devices. These changes are frequency dependent and are greatest at or near the current maxima or the current nulls.

Measurements of $|\Gamma_1|-|\Gamma_2|$ are shown for two different connections of highly reflecting devices with 14-mm connectors. These measurements are used to estimate the changes in normalized joint resistance at the connector. Similarly, measurements of $\arg(\Gamma_1)-\arg(\Gamma_2)$ are shown for two different connections. These measurements are used to estimate the changes in normalized reactance. For the devices shown, the changes primarily occur at the current maxima, which means the changes are in the resistance and inductive components of the connector joint.

## Acknowledgment

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[1] W. C. Daywitt, "A simple technique for investigating defects in coaxial connectors," pp. 460–464, this issue.

# A Simple Technique for Investigating Defects in Coaxial Connectors

WILLIAM C. DAYWITT

***Abstract* —This paper describes a technique that uses swept-frequency automatic network analyzer (ANA) data for investigating electrical defects in coaxial connectors. The technique will be useful to connector and ANA manufacturers and to engineers interested in determining connector characteristics for error analyses. A simplified theory is presented and the technique is illustrated by applying it to perturbations caused by the center conductor gap in a 7-mm connector pair.**

**Key terms:** ANA, coaxial connector, error analysis, stepped-frequency measurements.

## I. Introduction

Most analyses underlying microwave measurement procedures assume ideal connectors at the various measurement ports, although it has been recognized for some time that errors due to this idealization would have to be accounted for sooner or later. With computerization and greater sensitivity and stability, modern systems are now at that point. For example, if a swept-frequency reflection measurement of an open circuit not used in the automatic network analyzer (ANA) calibration is performed, then the measured reflection coefficient magnitude often varies in a strongly oscillatory manner below and above unity magnitude, while the obvious result should be a magnitude that remains below unity and slowly diminishes monotonically with frequency. This type of result has been noted by a number of ANA users. Studies [1] have shown that the oscillatory phenomenon just described is due to connector loss at the joint in the connector pair where the center conductors from the two connectors comprising the pair meet, and also that the oscillations can be used to determine the magnitude of that loss even in the presence of considerable ANA error.

Recent investigations indicate that reactive defects at the same joint in the connector pair cause phase variations similar to the magnitude oscillations, and that the envelope of these variations can be used to determine the magnitude of the reactance responsible for the variations.

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