

A High Isolation Dual Signal Probe Technology

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Abstract – We describe a new dual signal probe and vector network analyzer (VNA) calibration standards providing high isolation between signals. Previously existing probes and standards may exhibit high coupling making them unsuitable for use with conventional VNAs. The new design significantly reduces the signal-to-signal coupling of the probes and standards enabling improved calibration and measurement to beyond 40 GHz.

I. INTRODUCTION

Dual-signal microwave probes find use for both two-port measurements for structures with in-line pads and for multiport measurements particularly where adjacent signals combine for differential excitation.

In-line pads are often used in sacrificial wafer scribe streets allowing verification (for example) of transistor performance while conserving space otherwise useful for producing sellable semiconductor. While more traditional two-port measurement configurations using opposing ground-signal-ground (GSG) patterns provide better results and are more understandable, the economics of high-volume manufacturing make the compromise of in-line structures such as the configuration shown in fig. 1 worth-while.

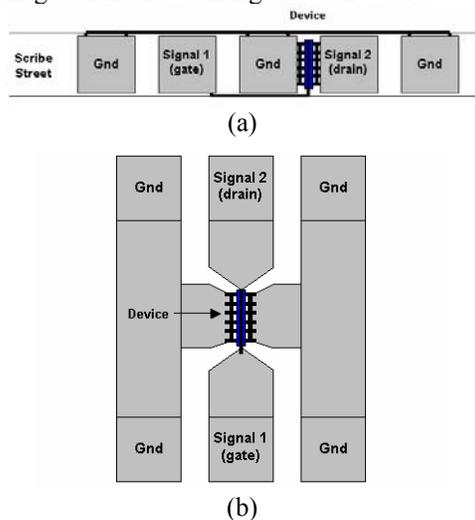


Fig. 1. In-line GSGSG and opposing GSG pad configurations.

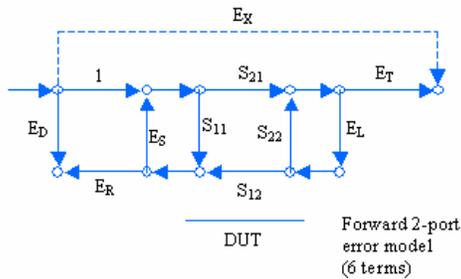
A number of multi-port configurations also take advantage of probes with combined signals. Those doing design and debug of differential circuits in particular find it convenient to combine pairs of signals on a probe and with adjacent pads. In application these pairs of signals conduct equal amplitude but opposite phase signals – known as balanced signals. Often the circuit layout will have either a GSGSG or GSSG pad configuration at the input and output.

In this paper we will examine the necessity for high isolation in dual-signal probes and standards to enable accurate measurement, consider what design elements are needed to achieve high-isolation, and present a new dual-signal probe technology with dramatically improved performance over previously existing probes.

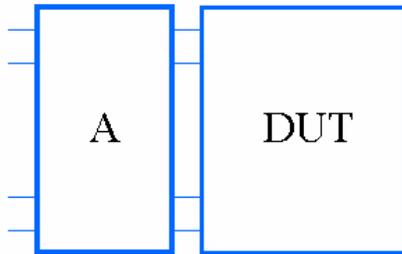
II. ERROR MODELS AND THE NEED FOR ISOLATION

When making vector network analyzer (VNA) measurements with GSGSG or GSSG pad configurations, calibration and measurement accuracy is affected by coupling between the signals. Standard 12-term VNA error models expect essentially uncoupled ports, allowing only simple isolation correction that is useful for internal VNA port leakage but cannot model coupling that varies with device-under-test (DUT) input impedance. This more general coupling is the usual case and is typified by the simple model of capacitance between signals at the probe-tip.

The 16-term error model [1]-[2] would be able to properly model coupling in the dual signal probes but is not generally available in commercial VNAs. One reason for this is that it is not normally useful for the traditional opposing probe setup where the coupling is a function of probe-to-probe spacing.



(a)



(b)

Fig. 2. The forward half of the 12 term error model is shown in (a). The isolation term E_x is independent of the DUT behavior. A general error model is shown in (b) after separately accounting for switching terms. The errors for the two-port calibration are fully contained by one four-port network. This model is general and allows for any type of coupling (within the context of modes supported by S-parameter corrections).

Since the spacing may vary for different calibration standards or DUTs the coupling error term is not constant and the best practice is to ignore it and opt for probes that insure that the uncorrected error is adequately small. It of course would be possible to implement the 16-term error model calibration and correction in software external to the VNA. A similar approach has been proposed for the multiport case [3] but again the multiport analyzers do not support the coupled-mode error model.

The published methods proposed for the two-port 16-term error model also all assume the availability of uncoupled, simultaneously connected, single-port standards. In the dual-signal probe case a dual standard must connect simultaneously to both ports and the standard itself can be a source of signal-to-signal coupling. We are not aware of an algorithm for the two-port case that addresses coupling in the standards.

Until alternative calibration approaches become more practical we are left with making the probes and the standards as compatible as

possible with the available error models. This means that both the probes and standards need to have high isolation. A practical goal is to exceed 30 dB isolation between signals for the dual-signal probe and standard combinations. This begins to approach the behavior of state-of-the-art probes in the opposing configuration of Fig. 1 which often achieve 50 dB isolation between signals up to 50 GHz.

III. HIGH ISOLATION CALIBRATION STRUCTURES

For calibration, the structures that are needed are generally highly reflective elements, lines of different lengths and a terminating structure that minimizes reflections back to the network analyzer ports. Typically these structures are open, short, coplanar waveguide lines of various lengths, and the load. Care must be used when designing and using these structures for calibration – especially when the error model for the connection to the calibration structures is less than the full 16 terms.

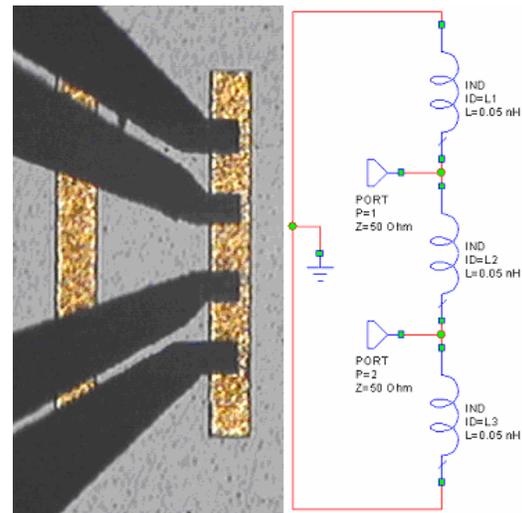


Fig. 3. Overly simple simultaneous short standard and its equivalent circuit. A 50 micron wide bar typically has about 0.5 pH per micron of length. GSSG-100 values are shown.

A common structure that is used for the shorting reflect is the bar short and is shown in fig. 3. The equivalent circuit illustrates that the inductance is not just between the signal and ground but is of the entire bar. This bar connects the signal to signal and signal to ground and both inductors are part of the measurement for calibration. The actual termination of a signal on the shorting bar

is given by the signal1-to-ground inductance, L , in parallel with series connection of L (signal1-to-signal2) and the parallel connection of L (signal2-to-ground) and 50 ohms (the other port impedance) and is given by:

$$Z_{term} = j\omega L \parallel (j\omega L + 50 \parallel j\omega L) \quad (1)$$

$$Z_{term} \cong j\omega \frac{2L}{3} \text{ for } \omega L \ll 50 \quad (2)$$

Use of this value with the standard techniques will provide good results. Ignoring the parasitic loading would introduce an error of $L/3$. Use of this incorrect value would result in an incorrect calibration causing potentially erroneous measurement results.

Another structure that could be used for the short for a GSSG configuration probe is that of two bars that connect each signal to only its neighboring ground with a gap between the signals. In this two bars with a gap case, the capacitance between the two signals could also cause an error and the unconnected grounds would allow undesirable modal behavior (slot mode) [4].

A shorting calibration structure with much better performance for both the GSGSG and GSSG configurations is that of the offset short that is discussed in [4] and shown in fig. 4.

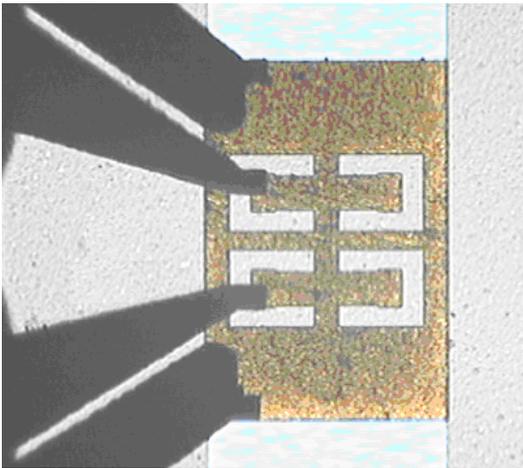


Fig. 4. A high-isolation GSSG dual short structure using the methods discussed in [4].

The open structure can suffer from unaccounted for behavior as well. Unshielded pads on a substrate will have capacitance between the signals so a better structure is that of pads

surrounded at least partially by ground. Having the line of sight from pad to pad interrupted by ground significantly reduces the pad to pad capacitance through electrostatic shielding. Probes in air also provides a good open but maintaining the consistency of pad configurations between each of the calibrations structures is desirable.

For the load, thru and line structures the characteristic impedance of each is designed so that the reflections are minimized. Even still, other sources of error need to be designed out. For instance, an on-wafer load for a GSSG configuration with no ground interposer and 100 micron pitch, exhibited a pad-to-pad capacitance of around 10fF. Even though small, the load impedance will be modified by 2.5 percent or -32 dB at 15 GHz and just under 10 percent or -24 dB at 40 GHz.

Without the native capability of the coupled error model, the reflect structures used for a calibration are one port devices even though their characteristics may be much more. As long as this behavior is measured or carefully determined, the calibration can be considered good. If on the other hand, anything other than the 12 term error model is used, the two port behavior of the calibration structures should be determined.

IV. A HIGH-ISOLATION DUAL-SIGNAL PROBE

For design purposes the wafer probe can be considered in three sections: connector, coax and tip. The connector and coax sections typically have very high isolation. The tip, however, inherently has the two signals in very close proximity perhaps using a shared guided wave structure so the assumption of high isolation cannot be made. [This is a place where the two port behavior of the calibration structure is useful in determining the crosstalk of a dual signal probe as distinguished from the standards.]

Dual signal probe tips generally come in two varieties: contact fingers in air or on a dielectric, or the flexible dielectric microstrip recently used for high-performance GSG probes [5]. The overall probe structure is ideally a smooth electrical transition from the coax to the DUT guided-wave structure (such as CPW) and is designed for minimal reflections at the internal

and external probe transitions: connector to coax, coax to tip, and tip to DUT. Both varieties of probe tips have attributes that contribute to crosstalk between the signals. Considering the best case of isolation in the GSGSG configuration (or alternatively GSSGSG), the coplanar tip has either a coupling path through the substrate or a shared ground or both.

When looking at the conventional GSGSG coplanar finger probe tip, the isolation discussion for the open calibration structure in the previous section may be used to predict the isolation between the signal paths. Since the line of sight from signal one to signal two is blocked by a central ground the isolation should be good. However, the coupling path is changed when the probe is used in its intended environment. The affinity for the electric field to exist in a higher dielectric material means that close to the tips of the wafer probe, the path is no longer line of sight but direct and through the dielectric.

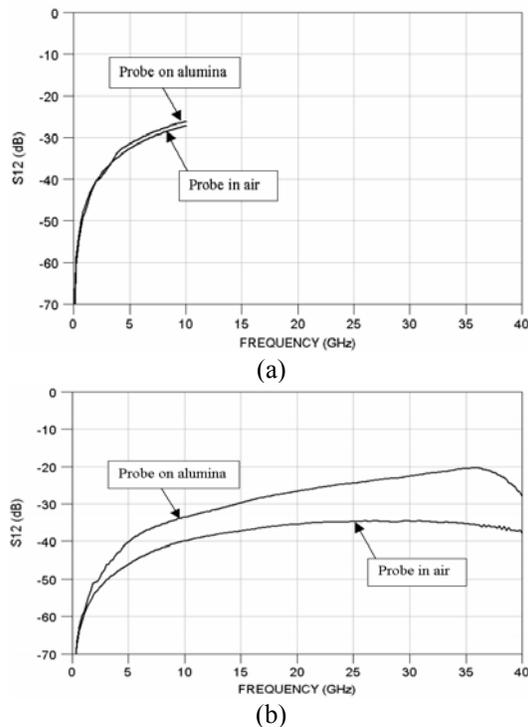


Fig. 5. Crosstalk performance of conventional probe with contact fingers in air for (a) GSSG and (b) GSGSG 150 micron pitch configurations.

Two cases are shown in fig. 5: probe in air and probe just contacting bare alumina. The measurement on alumina illustrates the contribution of the calibration substrate as a route around the central ground finger for the GSGSG case.

The amount of crosstalk predicted for two microstrip lines over a common ground plane may be estimated by

$$Xtalk \cong \frac{1}{1 + \left(\frac{D}{H}\right)^2} \quad (3)$$

where D is the center-to-center spacing of the transmission lines and H is the height over the shared ground plane (see for example [6]). The crosstalk is modeled using a Gaussian current distribution on the ground plane, induced by one signal and sensed by the other. From this simple equation a 100 micron pitch GSGSG probe that uses this technique could expect isolation that is 40 dB from signal-to-signal. However, this does not include a transition to wafer nor to the coaxial transmission line. Design limitations exclude the use of an electrostatic shield between the signal fingers for the GSSG configuration with less than 150 micron pitch.

The dual-signal Infinity probe, shown in fig. 6, makes use of the inherent (higher) isolation of the microstrip structure. With careful attention to the design of the transitions, these probes surpass the predicted response listed above.

V. CONCLUSION

Isolation results for the dual-signal Infinity GSSG and GSGSG probes are shown in fig. 7. We have achieved high isolation exceeding 30 dB to 40 GHz for the GSSG configuration and exceeding 40 dB to 40 GHz for the GSGSG configuration. We believe that this represents an extension to the state-of-the-art, enabling more precise measurement of in-line two-port and multi-port networks.

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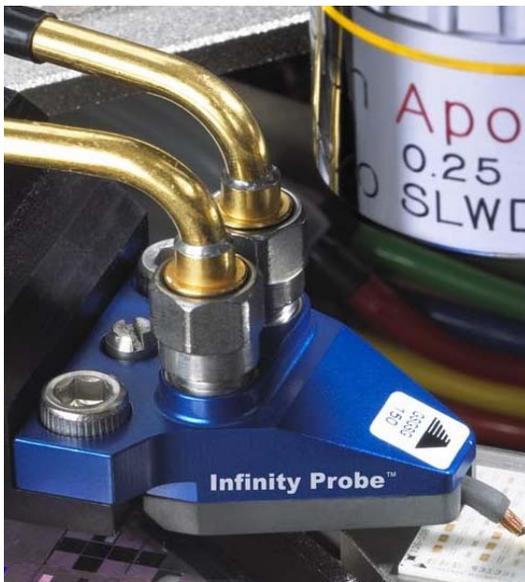


Fig. 6. Image of the new dual-signal Infinity probe.

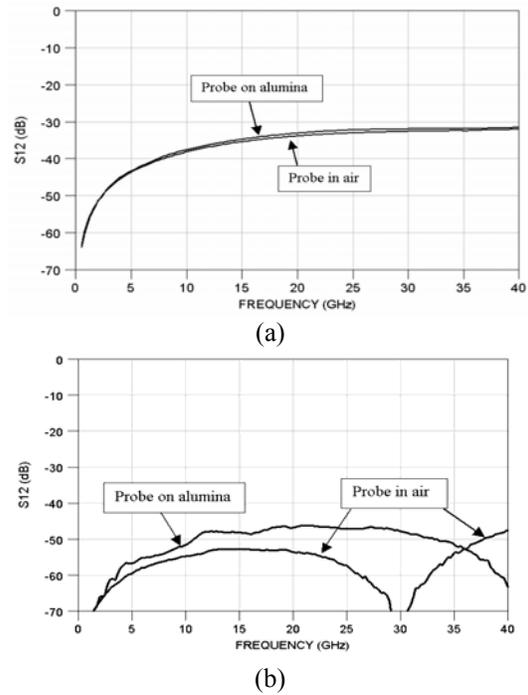


Fig. 7. High-isolation dual-signal Infinity probes with (a) GSSG and (b) GSGSG 150 micron pitch configuration.