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Challenges in 10GHz Transimpedance Amplifier (TIA) Production Testing

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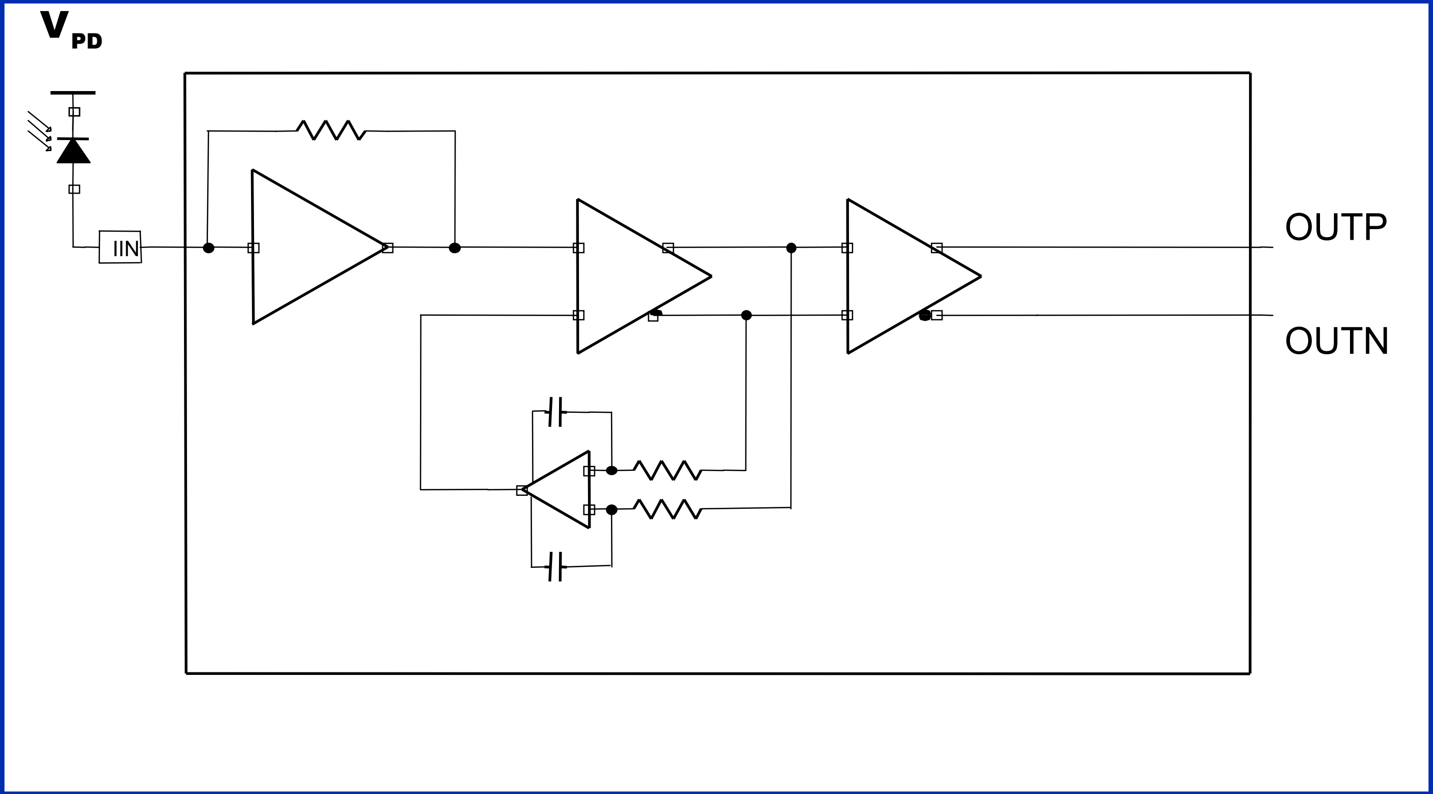
10GHz Transimpedance Amplifier

- 10GHz Transimpedance Amplifier (a.k.a.,TIA) are used for SONET/SDH OC-192/STM-64 and 10 GbE applications. 10GHz TIA are usually used in die form.



Key Specs for 10GHz TIA---AC

- Key AC parameters
  - Transimpedance (Z_T, ranging from hundreds of ohms to tens of Kilo ohms). Z_T is the gain from small input signal (~10uA order) to output voltage (e.g. 10mV output generated from 10μA input for 1Kohm Z_T). Z_T Can be measured in two ways:
    - Time domain

      Output amplitude divided by input current at specified data rate (e.g. 1Gbps). Build 1Kohm resistor close to input (IIN) probe on probe card. Need oscilloscope and pattern generator.
    - Frequency domain

      Calculated from S parameter. Use regular microwave probe at IIN and OUTP/OUTN. Need Vector Network Analyzer (VNA).
  - Bandwidth (BW ~10GHz). Need VNA. 3dB down from reference point using S_{21} or Z_T.
  - S_{22} (-15dB order). Related to output impedance. Need VNA.

Key Specs for 10GHz TIA---AC and DC

- Key AC parameters(continued)
  - Input Referred Noise (I_{NOISE} ~ 1.0μA order). Output noise referred to input by dividing Z_T . Output noise measured using power meter. I_{NOISE} is related optical sensitivity. Some datasheet shows Input Noise Current Density ($I_{DENSITY}$ ~ 10 pA/√Hz order), which is Input Referred Noise divided by square root of bandwidth.
  - Output swing in limiting mode. Need oscilloscope.
  - Other AC parameters like jitter and group delay etc.
- Key DC parameters
  - Power Supply Current (I_{CC}).
  - Output Offset (V_{OFFSET}) and input bias voltage (V_{BIAS}).
  - Received-signal monitoring current (I_{MON}) or voltage(V_{MON}).
  - Other DC parameters like DC compensation parameters etc.

Methodology in 10GHz TIA Testing

- Exit on fail to reduce test time.
- DC parameters tested first due to short test time.
- Use frequency domain for Z_T measurement.

  VNA data are extracted for S_{22}, Z_T, and BW. Key is the accuracy of VNA measurement in broadband range (MHz to tens of GHz).
- Power meter to measure output noise and calculate I_{NOISE}.
- Oscilloscope to test output swing in limiting mode.

Challenges in 10GHz TIA Production Testing

- Frequency domain for Z_T measurement.
- Accuracy of VNA measurement in broadband range.
- Accuracy of power meter and oscilloscope testing.
- All calibration, correlation and test are performed in probing environment (probe card + automatic prober).

Z_T in Frequency Domain

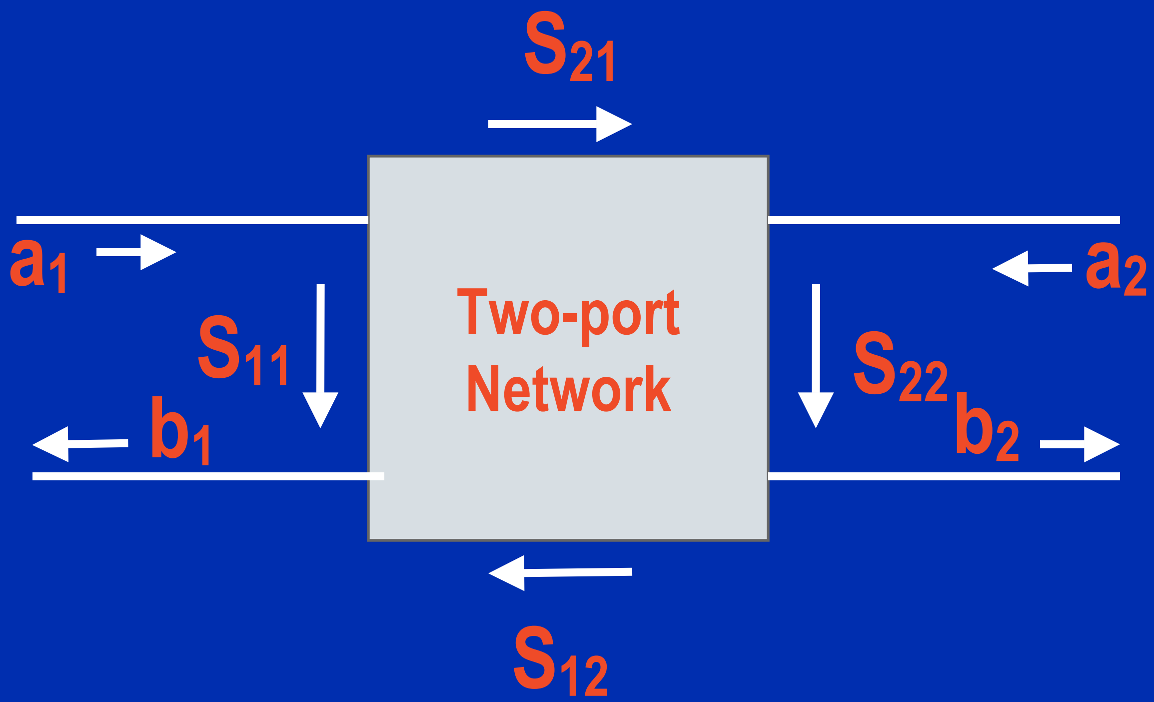
$$Z_T = f(S_{XY})\ ?$$

Two-port Network and S Parameters

- Two port network

$$b_1 = S_{11} * a_1 + S_{12} * a_2 \qquad (1)$$

$$b_2 = S_{21} * a_1 + S_{22} * a_2 \qquad (2)$$

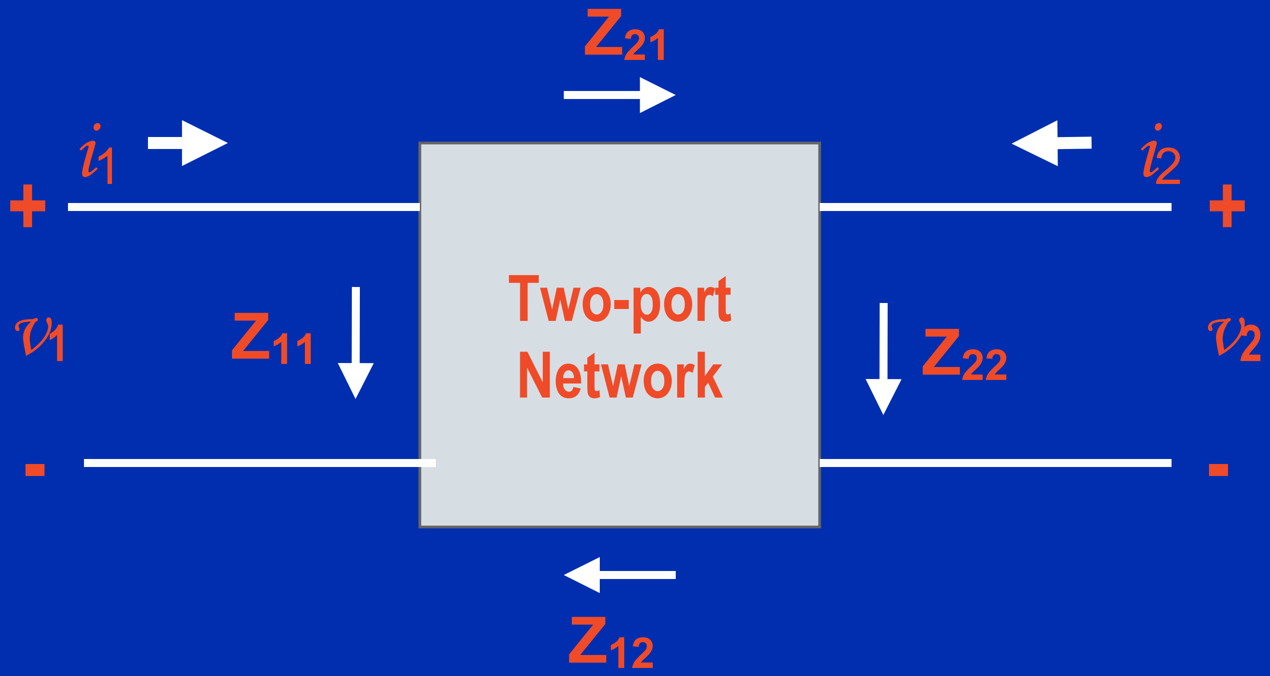


Two-port Network and Z parameters

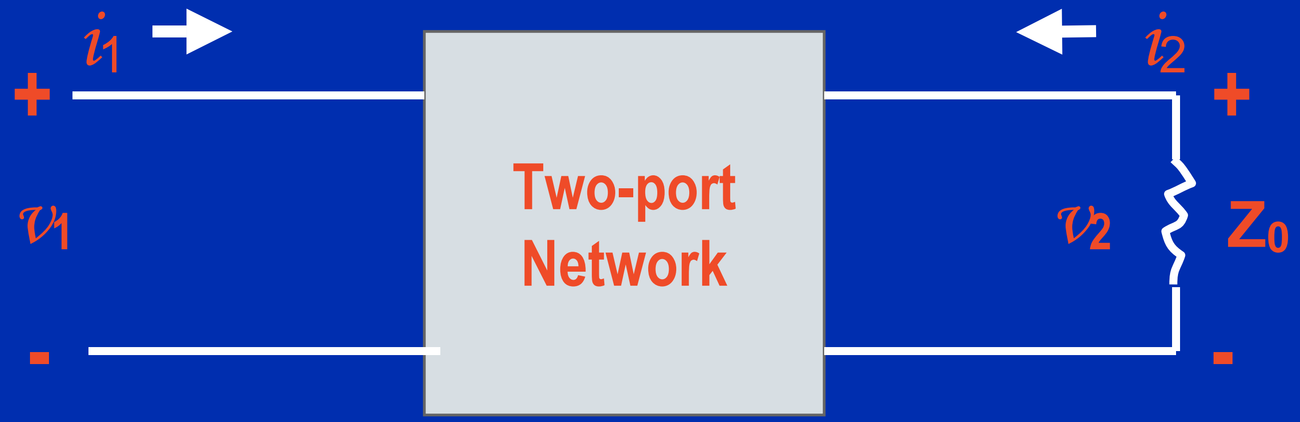
- Two port network

$$v_1 = Z_{11} * i_1 + Z_{12} * i_2 \quad (3)$$

$$v_2 = Z_{21} * i_1 + Z_{22} * i_2 \quad (4)$$



Z_T Formula from S parameters



- $i_2 = -v_2 / Z_0$ **(5)**

Use (5) in (4) and rearrange,

$$v_2 / i_1 = Z_T = Z_{21} / (1 + Z_{22} / Z_0) \qquad \textbf{(6)}$$

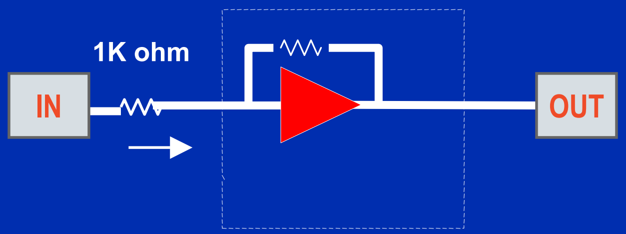
Use $Z_{21} = Z_0 \frac{2 * S_{21}}{(1 - S_{11})(1 - S_{22}) - S_{12} S_{21}}$ $Z_{22} = Z_0 \frac{(1 - S_{11})(1 + S_{22}) + S_{12} S_{21}}{(1 - S_{11})(1 - S_{22}) - S_{12} S_{21}}$ in (6),

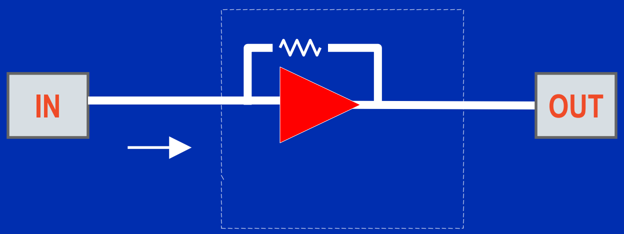
$$Z_T = Z_0 * S_{21} / (1 - S_{11}) \qquad \textbf{(7)}$$

Z_T Formula Verification---Setups

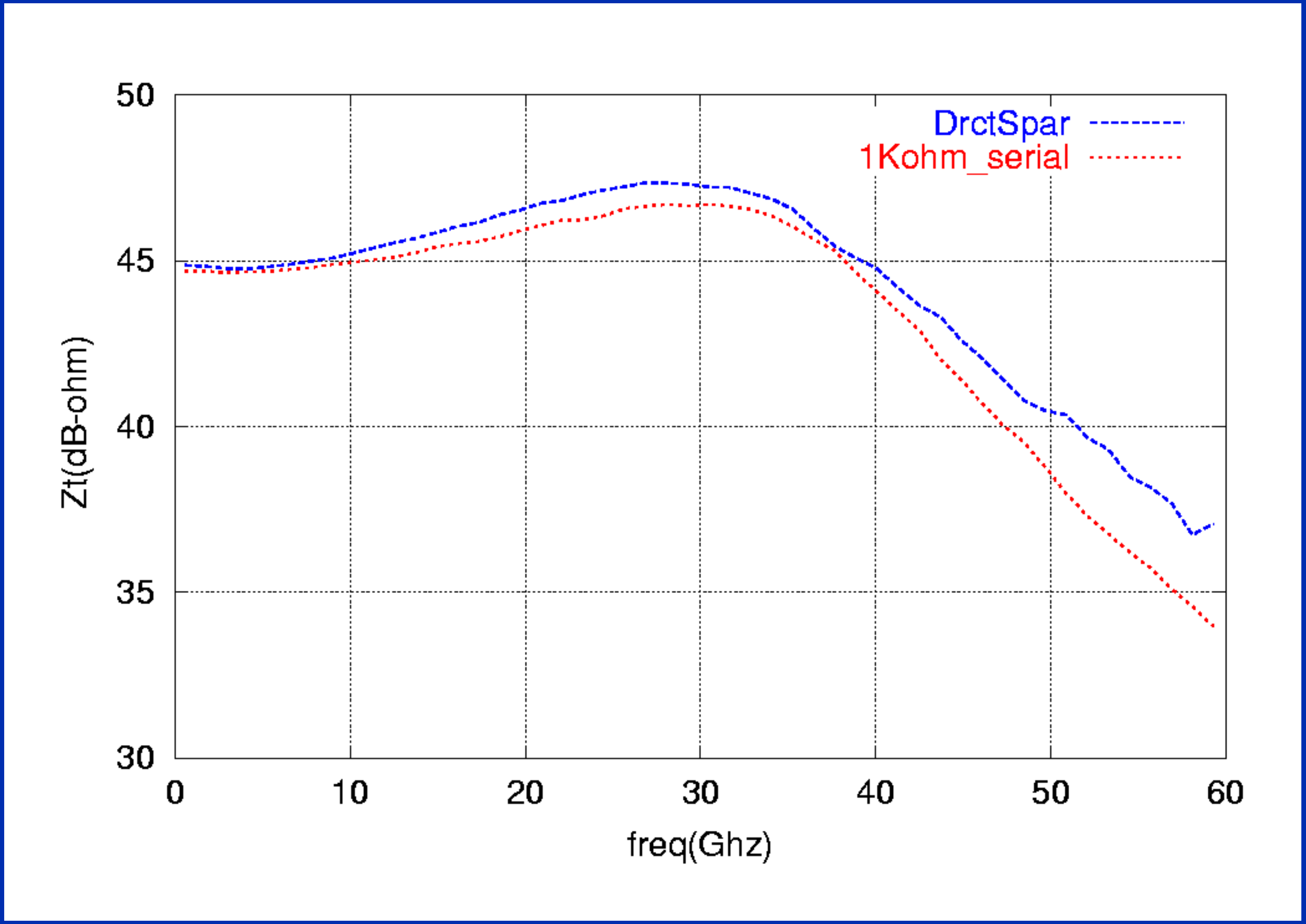
- Use 1 kΩ resistor in series to convert input voltage swing to current swing into TIA. See diagram on the left.
- Use $Z_T = Z_0 * S_{21}/(1 - S_{11})$. See diagram on the right.
- Both methods are used to test 40GHz TIA. Results

  track well over frequency, closer below 10GHz.





Z_T Formula Verification---Data



Data Source: Charles Wu, Vitesse Semiconductor Corp.

Accuracy of Test Equipment and Setup

- VNA accuracy in broadband range.
- Power meter accuracy.
- Oscilloscope accuracy.
- Setup calibration

Measurement Errors and Corrections

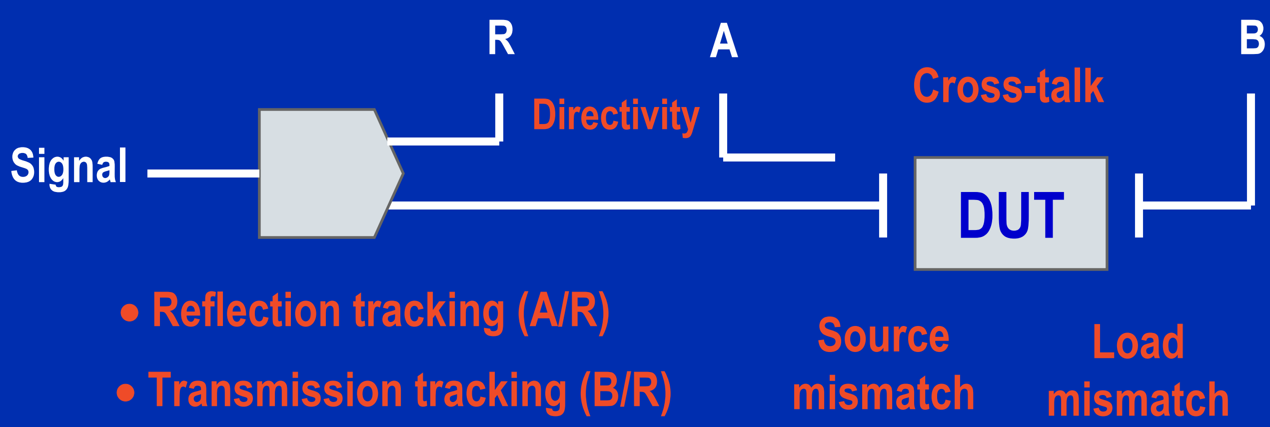
- Systematic Errors
  - Consistent and repeatable.
  - Reduced by calibration.
- Random Errors
  - Random in nature.
  - Reduced by averaging.
- Drift Errors
  - Measurement drift due to temperature and humidity etc.
  - Keep constant ambient temperature and humidity.
  - Reduced by periodic calibration.
- Correlation
  - Validate setup, hardware and software etc

Vector Network Analyzer Errors

- Systematic errors
  - Causes: Imperfections in the test equipment and test setup.
  - Characteristics: Repeatable and predictable, and therefore can be removed through calibration.
  - Six types of errors
    - Directivity and cross-talk errors
    - Source & load impedance mismatches
    - Errors in reflection and transmission tracking
  - Six errors are true for both forward and reverse direction.
  - Calibration: An error model established on measuring known standards.

VNA Errors---Systematic Errors

- Diagram for systematic errors



VNA Errors---Random Errors

- Random errors
  - Causes: Instrument noise; Switch repeatability; Connector repeatability.
  - Characteristics: Random and not predictable.
  - How to reduce random errors
    - Increasing source power. S_{21} need to be in linear mode(small signal). S_{11}, S_{22} can use higher power.
    - Narrowing IF bandwidth. Trade-off between test time and accuracy.
    - Averaging over multiple sweeps. Balance between test time and accuracy.

VNA Errors---Drift Errors

- Drift errors
  - Causes: Temperature and humidity variation.
  - Correlation wafer can catch drift errors.
  - How to minimize drift errors
    - Keep ambient temperature and humidity stable in test environment.
    - Run periodic calibration if ambient condition changes (e.g., temperature drift > ±5°C).

VNA Calibration

- Two basic types of error correction
  - Response calibration
    - Normalized measurement.
    - Correcting errors in reflection and transmission tracking.
  - Vector error correction
    - One port calibration accounts for three errors in reflection measurement: Directivity, Source match and Reflection tracking.
      - Assumes good termination on the other port for a two-port device.
      - Three known standards: OPEN, SHORT and LOAD.
    - Two-port calibration corrects all major systematic errors.
      - Short-Open-Load-Through(SOLT) calibration and Through-Reflect-Line(TRL) calibration are two popular two-port calibrations.
      - Isolation (cross-talk) is usually omitted as the measurement are made near VNA's noise floor.
      - Both use 12-term error model.

VNA Calibration---OSLT

- More on SOLT
  - Preferred calibration in coaxial applications.
  - Ideal “S”: Unity reflection with 180 degrees of phase shift.
  - Ideal “O”: Unity reflection with no phase shift.
    - Lift probes up more than double the probe spacing above a bare spot on substrate;
    - Or use OPEN pad structures.
  - Ideal “L”: Perfect termination over a broad frequency range.
    - Use a pair of 100ohm for GSG probe;
    - Or single 50ohm for GS probes.
  - Ideal “T” : Maintain constant impedance ($Z_0 = 50\Omega$).

VNA Calibration---TRL

- More on TRL
  - True TRL calibration requires a VNA with four receivers
  - “T” either a THRU or a short transmission line (TL).
  - “R” requires identical reflects on both ports.
    - Either SHORT or OPEN can be used.
  - “L” NOT the same length as the “T" . Z_o of “L” is the reference impedance for the measurement.
  - Variations include Line-Reflect-Match (LRM) calibration and Through-Reflect-Match (TRM) calibration.
  - Multiple lines are required for broad frequency.

    A single line covers 8:1 frequency range.
  - Optimal length of LINE standard is ¼ wavelength at the

    geometric mean of the desired frequency span ($\sqrt{f_1} * \sqrt{f_2}$)

Calibration Wafer

- Production automatic prober requires:
  - Repeatable pattern for alignment.
  - Need cal standards on 4/6/8 inch wafer.
- Cal standards on ceramic substrate used to validate and characterize cal wafer on engineering prober.
- To monitor the calibration process, a script is developed to record the data in each calibration step and compared to preset criteria.
- Operation procedure is established and released to manufacturing.
- Cal wafer covers multi products to cut cost

Accuracy of Power Meter

- Zeroing set the power meter for a zero power reading with no power applied to power sensor.
- Zeroing is needed before calibration and also recommended under the following conditions:
  - Ambient temperature change > ±5 °C.
  - Install a new power sensor.
- Calibration use a traceable power reference to set the gain.
- Run confidence check to verify the test path accuracy.

Accuracy of Oscilloscope

- Oscilloscopes usually have built-in self-calibration features, or compensation capability to enhance measurement accuracy.
- Warm up time. Refer to user manual for time duration. Use features only after the scope temperature has stabilized.
- Handle sampling modules with care.
  - Install or remove sampling module after the scope is turned off.
  - Run calibration or compensation after a sampling module is installed.
- Calibration or compensation is needed if ambient temperature, or humidity changes.

Guardbanding

- To deal with uncertainty of individual measurement.
- Assuming uncertainty of ε, the test limits can be guard-banded as follows:
  - Upper limit = Upper spec limit - ε;
  - Lower limit = Lower spec limit + ε;
- For Gaussian distribution, ε can be set at 3σ.
- Improving measurement repeatability helps to reduce guard band.
- Averaging can improve measurement repeatability, yet at the cost of test time.

Other Considerations

- Short cable for critical path.
  - Input (IIN) to VNA and Output (OUTP/or OUTN) to VNA.
- Connectors, cables and other accessories for AC test are required to have a bandwidth better than 26GHz.
- Utilize the built-in Bias -T with Port 1 and Port 2 of VNA for DC tests.
- Use more data points and more sweep time if test time permits.
- Correlation wafer to verify setup.
  - Used as “Golden” wafer for operators to validate calibrated setup.

Conclusions

- Consolidate S_{22}, Z_T, and BW testing on VNA.
  - Express Z_T in terms of S parameters and validate the formula.
- Errors of VNA and corrections are discussed.
  - Cal wafer for calibration.
  - Script to execute & evaluate calibration. Procedure is released.
  - Adjusting source power, IF bandwidth, data points, sweep time and averaging to optimize production testing.
- Accuracy of oscilloscope and power meter discussed.
  - Temperature compensation for oscilloscope.
  - Zeroing and calibration for power meter.
- Correlation wafer to validate setup and calibration.
- Guardbanding to minimize measurement uncertainty.

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Thank You

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