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Laser Optical In-Circuit Measurement System for Immunity Applications

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Abstract—**During immunity testing (ESD, EFT) of a digital circuit, the waveforms of critical signal nets need to be measured for analyzing the failure mechanism. However, it is difficult to measure the induced voltage in the circuit under test due to the unwanted coupling by the non-ideal shielding of the probe cable, especially, if large common mode currents are present. Fiber optical connection avoids this problem. Semiconductor lasers have frequently been used for converting the voltage into an optical signal. The paper shows novel implementations of powering the laser, leading to a small, low cost optical probe.**

Keywords- Susceptibility test, Optical link, EM coupling, Non-ideal shielding.

I. INTRODUCTION

During immunity testing voltages and currents are superimposed onto the normal voltages caused by the operation of the system. In digital circuits this can lead to bit flips or added jitter, in analog system it disturbs the signal. Using scanning methods [1] it is possible to identify the sensitive nets. As next step the voltages of the critical nets need to be measured while disturbing the system using e.g., ESD.

Monitoring the voltage on a PCB during ESD immunity testing is complicated because of the following reasons:

- Cabling from the circuit to the instruments will influence voltages and currents that are measured.
- The cabling, through its non-ideal shielding, will pick up additional signals that are not present in the circuit.
- The measurement instruments are endangered as they might be subjected to parts of the immunity fields or pulses.
- High voltage present in a circuit or a test setup might endanger operators or the instruments.

Different methods have been applied in the past to overcome these problems, examples are the use of differential probes. However, they are limited by the maximal common mode swing allowed and by the common mode rejection ratio that is insufficient in most cases.

Further methods are by attaching a heavily ferrite loaded (to reduce common mode currents [2]) semi-rigid cables to the circuit, e.g., via a 500 Ohm SMT resistor (to reduce circuit loading). In most cases one has to place the oscilloscope additionally into a shielded enclosure.

A. *Optical Link Based Measurement Methods*

A variety of fiber optic based methods have been described.

The principal reasons for the popularity of optical fiber based sensor systems include their small size, light weight, immunity to electromagnetic interference (EMI), passive composition (all dielectric), large bandwidth, higher sensitivity, and acceptable temperature performance [3].

Fiber-coupled interferometers such as the Mach-Zehnder interferometer, Michelson interferometer and Fabry-Perot interferometer have been implemented in the measurement of electrical parameters [4,5]. Polarization modulation-based techniques also have been implemented in high-voltage measurement [6,7]. Some commercial interferometer-based optical links are available, for example the wideband integrated optic modulator (400-03-C) from Srico Inc.[8], which is based on Mach-Zehnder modulators offers very high measurement bandwidth and sensitivity. However, the size of most electrical/optical modulators, especially active ones is relatively large for in-circuit measurement. Interferometer and polarization-based techniques have advantages in sensitivity over the intensity based optic sensor. However, the complexity of the modulator and demodulator circuitry, therefore the cost, are the trade-offs. On the other hand, optical power intensity based fiber optic sensor are inherently simple and cheap [9~10].

Semiconductor lasers offer good bandwidth, small size and low cost. However, they need a bias laser current. The paper describes different sensor implementations with emphasis on different bias methodologies.

II. DESIGN AND IMPLEMENTATION OF THE OPTICAL IN-CIRCUIT MEASURMENT SYSTEM

A. *Proposed Solution*

The basic circuit of the proposed measurement system is shown in Figure 1. It consists of a small in-circuit probe, optical receiver and fiber optic connection. In its most fundamental implementation no bias circuit is used for the laser. The probe needs to be powered by the circuit under test.

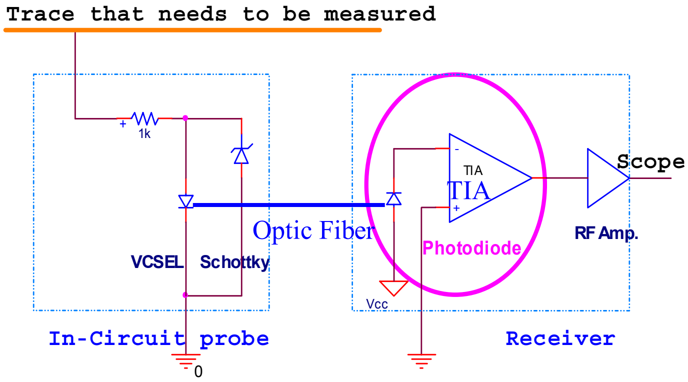

Figure 1. Most fundamental implementation, powering the laser by the circuit under test.

B. *Implementaion of The In-Circuit Probe*

The in-circuit probe is designed to be soldered in the measured circuit, as shown in Figure 2. A DIE vertical cavity surface emitting laser (5 Gb/s Ulm-photonics 0.8mA threshold current) has been selected. The AC-input impedance is about 1.5 kOhm (the VCSEL has a slope resistance of 400 Ohms) and it draws about 1 mA DC at 3V to ensure acceptable loading for most circuit. The active area of the probe (without landing pads for connecting it to a circuit) is less than 2 mm in diameter to minimize coupling.

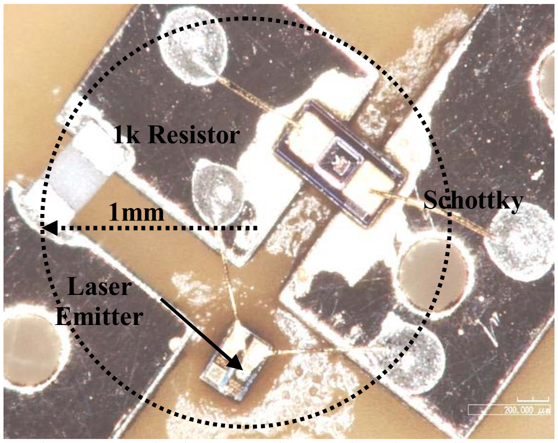

Figure 2. Probe layout and mounting the optic cable.

A 62.5µm/125µm multimode fiber optical cable is directly mounted onto the emitting window of the laser diode. The connector at the receiver side of the optic fiber cable is of type LC [11], which is compatible with the ROSA package of the selected photodiode.

C. *Optical Receiver*

Photodiode, amplifier, and power supply circuit compose the receiver. The photodiode (GaAs PIN type photodiode from ULM Photonics, 5 Gbps) offers a built-in transimpedance amplifier (TIA) and an AC-coupled output.

III. BIASING THE LASER

To avoid draining bias current from the circuit under test remote biasing is needed. Adding a photodiode in parallel with the laser diode and illuminating the photodiodes by a second fiber is an option (Figure 3). For preventing the bias voltage from affecting the DUT, the probe needs to be AC-coupled to the DUT.

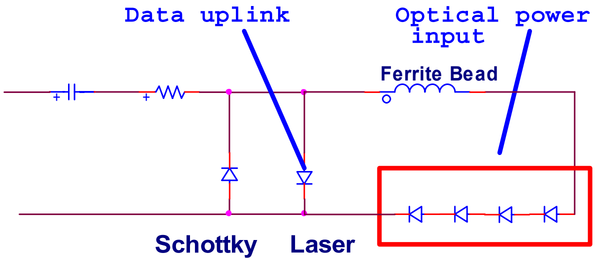

Figure 3. Probe circuit with optical remote biasing.

Resistive Wire Remote Biasing

Another option is using resistive wires. If the resistance per unit length is large enough, the wires will disturb the electromagnetic field [12, 13] little. However, close to the laser probe they still act as heavily resistively loaded antenna (wire: 400 Ohm/in, Marktek Inc.) thus they will introduce a current through the probe that needs to be suppressed by local filtering, see Figure 4.

To allow the probe DC-coupled to the measured circuit, additional circuits must be added to prevent the bias circuit from affecting the circuit under test. Figure 5 shows a possible solution. Since the bias voltage will cause a voltage offset at the measurement point, another voltage supply is added to cancel the offset voltage. Spice simulation shows the circuit works, but to implement this design, three resistive needs to be mounted to the probe, which will result a increasing of the probe size.

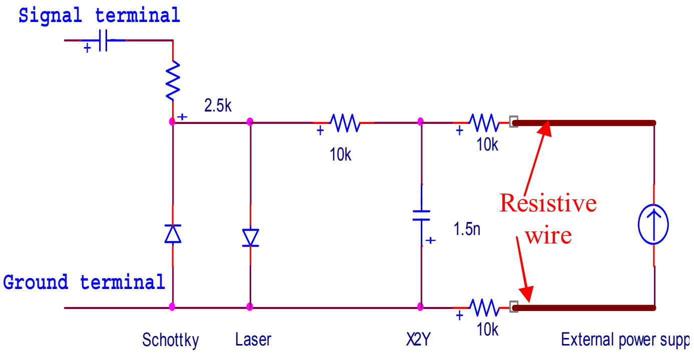

Figure 4. Probe circuit with resistive wire biasing.

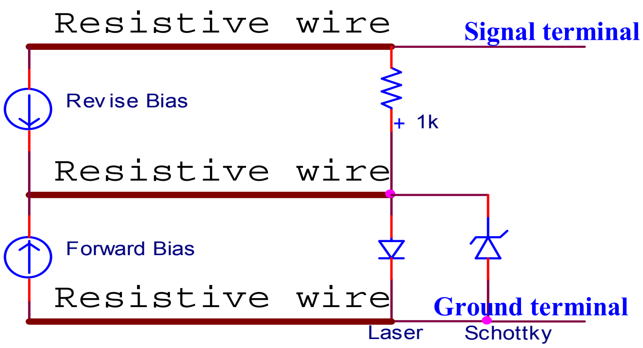

Figure 5. DC-coupled probe circuit with resistive wire biasing

A third option of biasing method is to add small batteries in the probe, as shown in Figure 6. The battery circuit omits the use of long power feeding wires, but at the expense of a larger probe circuit (more coupling) and limited life span of the batteries. As the batteries act as antennas, local filtering is needed. A Zinc cell offers 1.5 volts and capacity of 80mAh. Selecting a bias of 2mA, the life span of the cells can be calculated as (80mA/2mA=40 hours).

In the three proposed biasing methods, the resistive wire biasing one is the easiest to be implemented and used. The final system is based on this method.

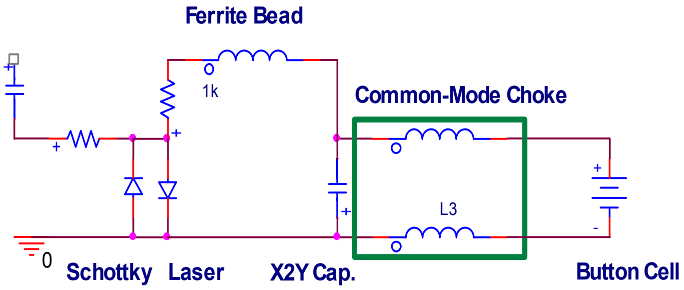

Figure 6. Probe circuit with button cell biasing

IV. CHARACTERIZATION OF THE SYSTEM

A. System Bandwidth Measurement Setup & Results:

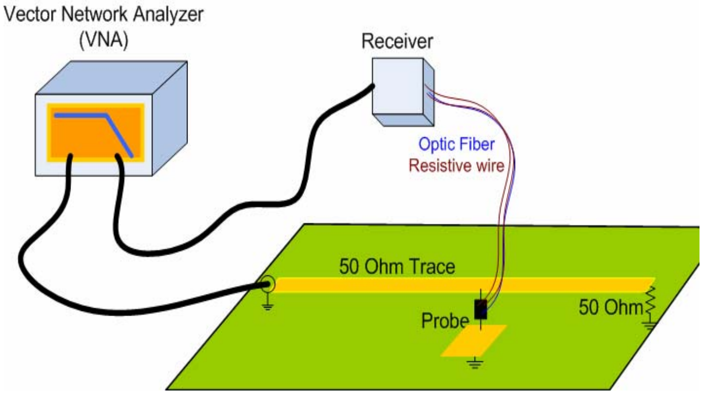

Figure 7. Bandwidth measurement setup.

The bandwidth measurement setup is shown in Figure 7. A 50 Ohm microstrip test board with SMA connectors is connected to one port of the VNA while the probe output is connected to the other port.

Figure 8 shows the result of the prototype laser probe on four out of six channels of the multi-channel receiver. The result shows very similar responses in each channel with a 2.5GHz bandwidth and a system 'gain' of$-12dB$. The lower frequency cutoff is determined by the coupling capacitor in the optical receiver.

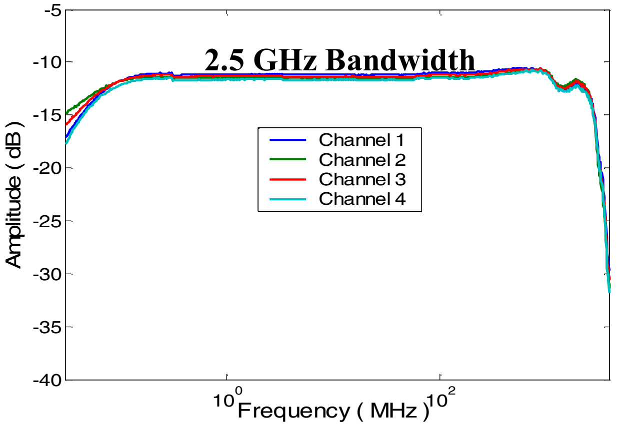

Figure 8. System frequency response.

B. System Dynamic Range:

If we take the voltage on the trace as input and the output of the photo diode as output, and assume biasing in the linear region, the transfer ratio can be described by Eq. (1):

$$\frac{V_{OUT}(f)}{V_{IN}(f)} = \frac{\eta_{Laser} \cdot \eta_{Mounting}}{Z_{IN}} R_{\lambda} \qquad (1)$$

Where:

η_{laser} is the slope efficiency of the laser, typically 0.5 *W/A;*

$\tau_{Mountingr}$ is the percent of optical power coupled by the optical fiber on the laser, usually around 50% if mounting is handled well;

$\rho_{Photodioder}$ is the responsivity of the photodiode, the typical value in the data sheet is *1.5 mV/μW;*

Z_{In} is the input impedance of the probe, which contains: the series resistor (R_{Series}), the reactance of the coupling capacitor (Z_{Cap}), and the slope resistance of the laser (R_{Slope}). The coupling capacitors value is 0.1μF, and the slope resistance of the laser is about 400 Ohm. Usually the series resistor can be selected in 1k~5k range, large series resistor will decrease the SNR.

The maximum linear input voltage at the probe is determined by the linear region of the current-optical power curve as shown in Figure 9. For best linear response, the bias point must be in the middle between the maximum linear current and the threshold current, which is 1.75mA. If we use a $2.5k\Omega$ series resistor, the maxim input voltage is $0.7mA \times (2.5k+0.4k) \approx 2V$, and the maximum optical output swing is $0.7mA \times \eta_{laser}=350\mu W$. If we further assume a mounting efficiency of 50%, the received optical power swing of the photodiode will be 175µW. For the photodiode selected the maximal non saturated optical input is 100µW (including the TIA). Therefore, the maximum output voltage is limited by the photodiode, which is 150mV. The maximum of the input voltage can be increased by using a larger value of the series resistor, refer to Eq.(1).

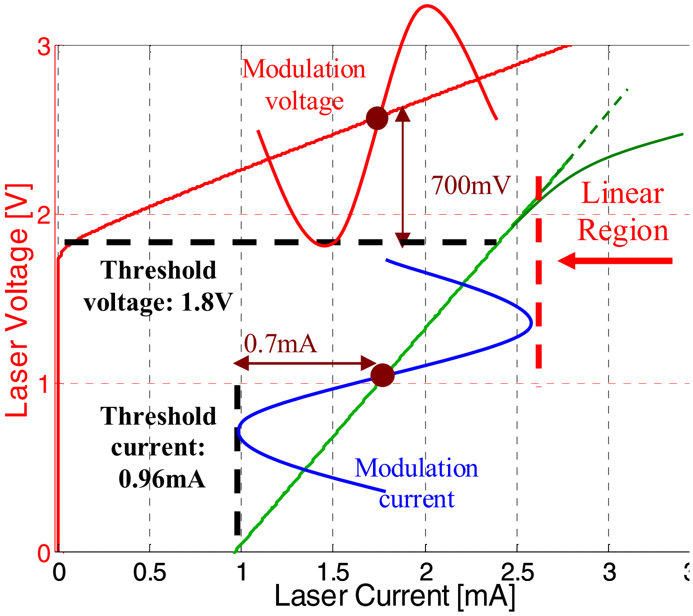

Figure 9. Optical power and voltage curve vs. input current of the laser.

C. *Noise Floor*

The noise in the probe is composed mainly by the switched power supply noise in the bias circuit. However, the fluctuation of the supply voltage causes very little current variation in the laser due to the high resistance of the resistive wire and the filter circuit. On the receiver side, the ULM-photonics photodiode has a noise equivalent power (NEP) of 1µW, which is equivalent to a $1.5mV_{(rms)}$ voltage by applying the responsivity. After the RF-amplifier, it gives about $6mV_{(rms)}$ noise voltage, which is very close to the measured system noise floor.

D. *Unwanted EM Coupling to the Probe*

Even a small circuit is not immune to unwanted coupling by a strong EM-field. A TEM cell was used to measure the coupling effect of the probe. The probe is open-circuited and is placed within the field of the TEM cell. Different probe orientations have been tested to obtain the worst case coupling. The coupling has been quantified by a VNA. Port 1 is used to create the disturbing field in the TEM cell, while port 2 is connected to the output of the optical receiver, see Figure 10.

Based on the geometry of the TEM cell the E-field is give by Eq. 2. By assuming uniform E-field, one can correlate the coupled voltage to the incident E-field as a *Coupling factor*:

$$\frac{V_2}{E} = h \cdot S_{21} \tag{2}$$

Where h is the height of the TEM cell

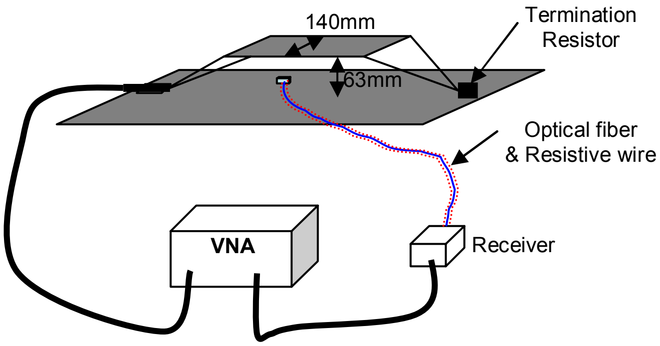

Figure 100. TEM measurement setup.

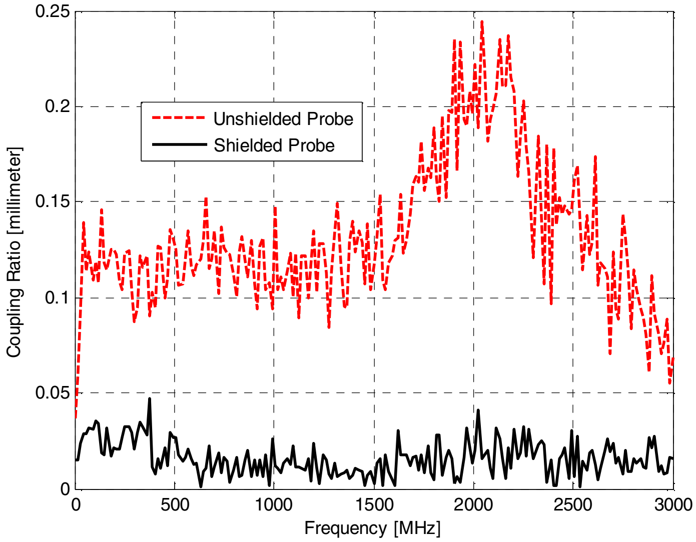

Figure 11. Probe coupling factor.

The coupling factor shown in Figure 11 describes the susceptibility of the probe to the incident E-field in the frequency domain. For example, assume there is strength of 1000V/m incident to the probe, in the worst case the coupled voltage is about 200mV if the probe is unshielded, which is too large to be used for practical measurement since it can cause about 0.5mA current change in the laser. After shielding is added, the coupled voltage is about 30mV, which is an acceptable value for immunity test

V. A PRACTICAL APPLICATION

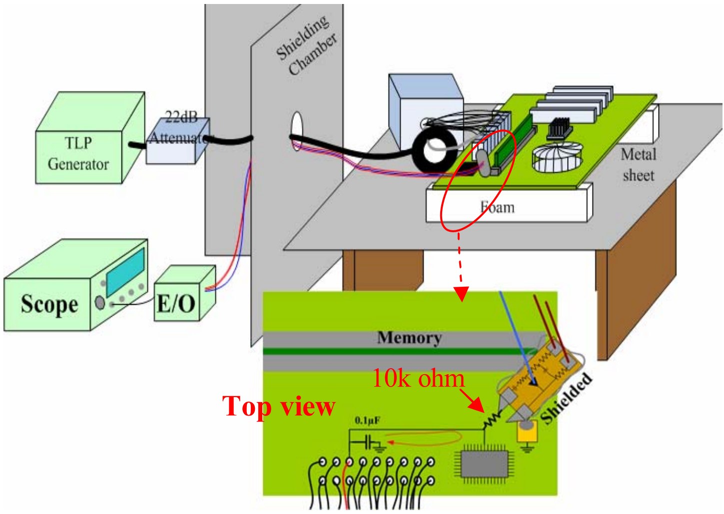

Figure 12. An application example.

This section presents an example that uses the laser optical system in an immunity test for a PC motherboard. The cable bundle that connects the motherboard to the power supply forms a good antenna.

A. Test using a Transmission Line Pulse (TLP) Generator

To locate the most sensitive net a system crash level test has been performed by injecting pulses from a transmission line pulses (TLP) to each cable in the bundle through a current probe (*Fischer F-130A*), as shown in Figure 12. The TLP generator discharges a two-meter long 50 ohm coaxial cable and produces adjustable high voltage impulses with about 900ps rise-time (10%-90%). The current probe has an insertion loss of 6 dB from 4MHz up to 450MHz.

The tests showed that the *PWRGD* line is the most sensitive line. When the motherboard is powered up the *PWRGD is* raised to 5V, which indicates 5V and 3.3V have stabilized. The *PWRGD* input is LVTTL logic with a threshold voltage in range of 0.8V~2V. If the threshold is reached due to induced noise the IC may sense it as a power no good signal, which will cause a system reset. In this particular implementation a filter capacitor has been placed on the input, however via a stub trace of about 3 nH inductance.

To demonstrate the crash level of this net, the 1µF filter capacitor is removed, and the induced voltage is measured by the optical probe. Due to the limited dynamic range of the measurement system, a 10k ohm resistor is soldered in series with the probe to decrease the input signal level. The "gain" of this setup is measured by using the same setup in the system bandwidth test, and a "gain" of -32dB is obtained. The system crashed when the TLP charge voltage reached 70V (negative pulse).

The result shown in Figure 13 is a comparison of the induced voltage that was measured by the laser probe and measured by the semi-rigid cable with 5kohms series resistor. One can see that the two results are close to each other, except that the result of semi-rigid measurement result contains the DC information of the *PWR_GD* pin. In this special case, the semi-rigid cable setup can produce very good measurement result, since the pulse is injected by the current probe, and the induced common mode current to the semi-rigid cable is very small

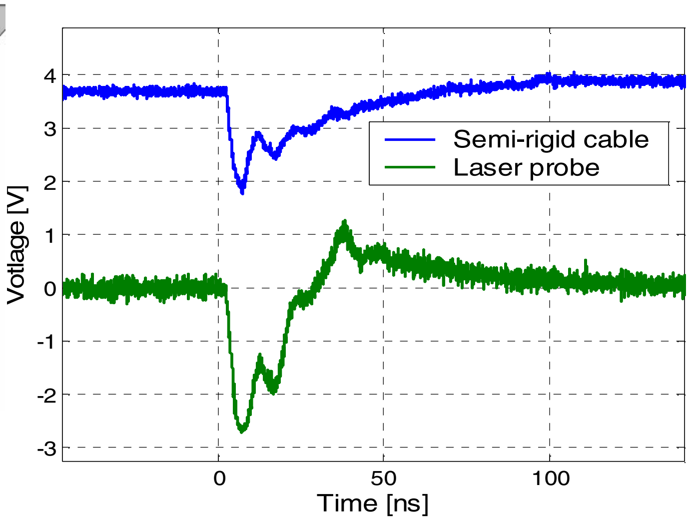

Figure 13. Voltage induced by a 200V TLP.

B. Test with an ESD Simulator

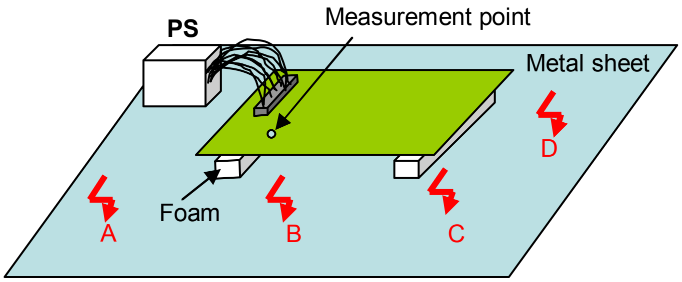

Figure 14. Disturbing the system by an ESD simulator.

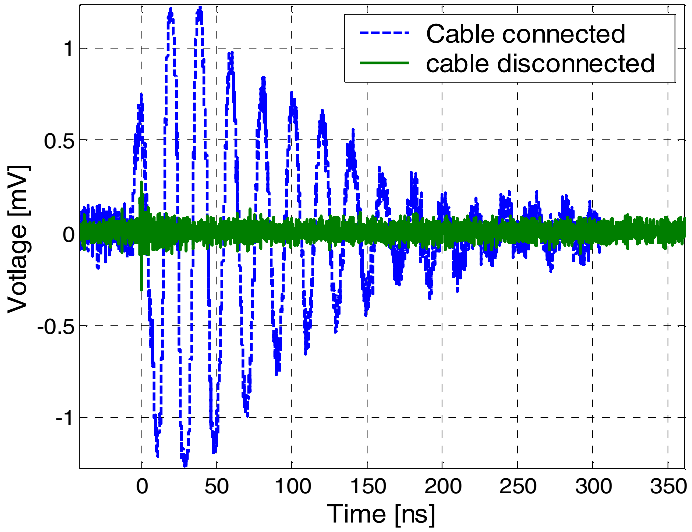

Figure 15. Induced voltage by ESD simulator.

Testing has also been done with an ESD simulator (KeyTek MZ15 E/C), and the discharges are applied to a horizontal metal sheet underneath the motherboard, as shown in Figure 14. The discharge points have a distance of about 15 cm to the edge of the board. The lowest crash level is 620 volt, when discharge is preformed at point D. The induced voltage is captured by the optical probe, see Figure 15.

The measurement result indicates the induced voltage's amplitude is about 1.2V, which seems not large enough to cause the crash. Besides the induced voltage in normal setup conditions a second graph is shown above. This was obtained by removing the power supply cable bundle. The data shows that direct coupling into the probe is not a relevant problem.

CONCLUSIONS

The paper discussed different options for biasing a laser diode used as electrical optical converter for voltage measurements in immunity testing. A variant using resistive wires was implemented. Testing showed sufficiently low circuit loading, 2 GHz bandwidth and low spurious coupling into the sensor. However, the linear response range of the laser diode and the optical saturation of the photodiode limit the system input and output voltage dynamic range. A compromise solution could be to add a voltage divider stage in the probe, i.e. a 10k to 1k divider. In this way, the maximum input voltage could reach more than 20V. However, it is not a good solution for measuring a low amplitude signal because the SNR is too low. In this case, different probes can be built for measuring different voltage ranges.

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