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Digital signal analysis of printed intelligence

Master Thesis

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Printed Intelligence
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ABSTRACT

Oulu University of Applied Sciences
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Fast signals such as square waves tend to distort on higher frequencies depending on materials electrical characteristics and lay-out design. Signal integrity is impacted by various electrical factors which can cause an unwanted behaviour or instability of the end product. For example, in case of a microstrip, characteristic impedance calculations are complicated; thus real-time measurements are required to verify signal integrity.

The main objective of the thesis was to study tens of MHz range digital signal integrity on traces produced by printed electronics on different substrate materials. Printed sample structures were measured, and level of signal distortion was analysed. Further evaluation was conducted according to simulation results and compared to real-time measurements. The thesis was completed as an independent study.

The thesis consisted of an overview of printing methods and materials focusing on inkjet printing method and materials used for sample circuits. The signal theory section was covered and presented in this document. Transmission line characteristics and low pass filter theory were in scope. Real-time measurement method and results were illustrated. In addition, simulation process was performed, and results were introduced. Measured values were compared to simulation results and evaluation was made.

Keywords: Printed intelligence, printed electronics (PE), ink-jet, Polyethylene terephthalate (PET), Polyimide (PI), silver ink, flexible hybrid electronics (FHE), integrated circuit (IC)

CONTENTS

1 INTRODUCTION

1.1 Thesis objectives

The thesis focus was to study signal behaviour on printed flexible substrates within frequency range of MHz rate. Selection for a suitable test method for measurement was studied on how to feed signal into substrate trace and take measurement at the end of the trace. Another target was to define method for analysing signal distortion level in signal path to original input signal. In addition, one of the objectives was to research simulation model for signal behaviour on printed traces and compare the final results to real-time measurement.

1.2 Hybrid flexible electronics

Printed electronics technology has advances. It is cost-efficient in mass production and the applications are lightweight and bendable. Also structure can be produced in various shapes which are challenging to manufacture by conventional electronics. However, PE technology has some disadvantages compared to conventional electronics.

Complex integrated circuits (IC) such as microcontrollers and memory are challenging to manufacture by printing. Also switching speed is limited with PE. On the other hand, hybrid approach combines PE advantages with conventional Si based benefits. Hybrid electronics or flexible hybrid electronics (FHE) has benefits: enhanced processing speed and capability with better transmission rate and they are lightweight. Furthermore, high volume FHE device production costs can be low in comparison with conventional printed wired board (PWB) manufacturing. Integrated applications of FHE can be smart labels, RFID flexible sensors, internet of things (IOT) and in-mold electronics [1] [4]

2 PRINTING METHODS AND MATERIALS

Complex integrated circuits (IC), e.g. microcontrollers and memory module fabrication, have technical challenges when printed thus making the level of functional complexity limited. On the other hand, hybrid approach combines PE advantages with conventional Si based benefits. Flexible hybrid electronics (FHE) has benefits of bendable shape and material can be stretched. Furthermore, high volume FHE device production costs can be low in comparison with convectional printed wired board (PWB) manufacturing. Integrated applications of FHE can be smart patch, near field communication sensors or internet of things (IOT) device. Applications can be manufactured by using flexible material as printing platform and assemble rigid components on the top of it.

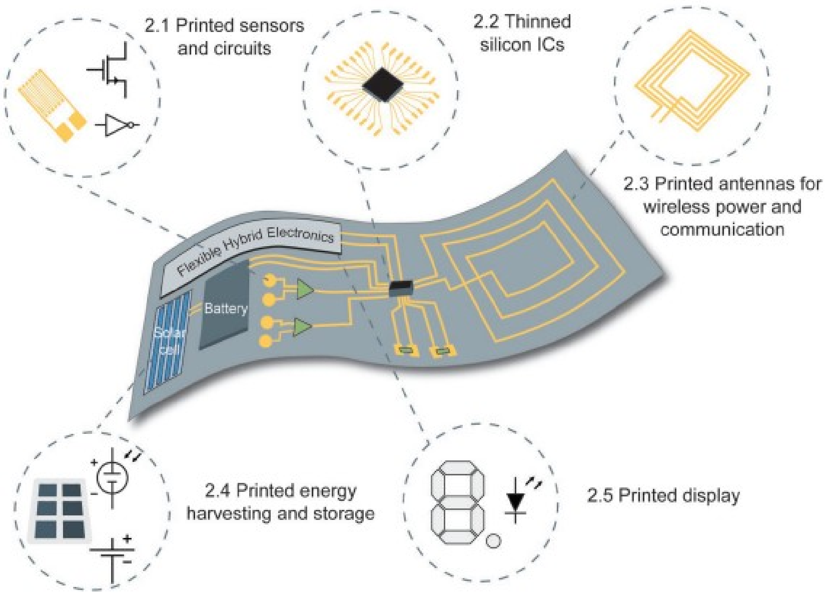


FIGURE 1. Illustration of flexible electronics system and surface mounted rigid components [4]

2.2 Printing electronics technologies overview

Printed electronics technologies can be divided into two main categories: contact and non-contact printing. During contact printing surface is in direct contact with printing element in contrast to contactless printing where print patterns are deposited into surface using spraying method. Gravure, offset and flexography printing are commonly used for high-volume production such as solar cell manufacturing. Screen printing is a feasible method for fabricating with thick layers or multilayer electronics [1]. Two of samples are made using screen printing.

Inkjet printing technology is covered in more detail in the following section. One of samples are fabricated using that method.

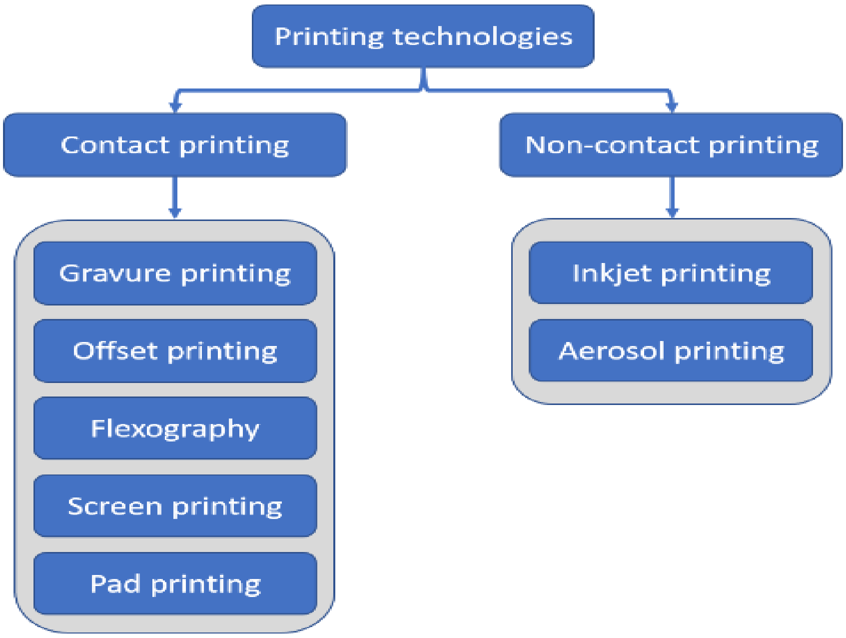


FIGURE 2. Schematic of Printing technologies [1]

PE technologies have a combination of advantages and disadvantages regarding throughput, resolution, printing speed and costs. For example, gravure technical printing speed is high 100 – 1000 m/min but initial fabrication preparations are expensive. [1]

2.3 Ink-jet method

Ink-jet printing is a digital non-contact printing method where liquid ink droplets are injected onto substrate through little nozzles. This printing method is applicable to versatile substrates and almost any form or shape including multilayer designs.

Furthermore, these methods are suitable for printing on flexible or rigid substrates and allows high printing quality of 2880 dpi. Additional advantages are that no pre-manufactured plates are needed and ink-jet printing saves material due to only targeted area on substrate is deposited. Therefore this technique is environmentally friendly and minimises material waste.[1][3]

Ink-jet printing is suitable for R&D purposes and special designs as samples can be manufactured one at a time when needed. In addition, conventional rigid components such as microcontrollers and memories chips can be combined with ink-jet printed design i.e., hybrid applications. Ink-jet method has some disadvantages: very high frequency applications are limited due to printing resolution and only planar surface designs are possible to produce. Also, nozzles clogging can be a problem during the printing process and printing throughput is lower compared to traditional manufacturing.

The method is fairly simple compared to other PE methods, but printing speed is limited. Printing speed is not limited as such but depends on required quality. Quality and electrical properties are depend also on interaction between ink and substrate during the printing process. In order to produce highly conductive structure, nanoparticles have to form solid and constant circuit route, i.e., conductivity is the same in every point in route. After printing design is treated by post processing so that pattern properties, for example conductivity, are optimal. Those procedures can be based on chemical or physical action.

Ink-jet printing requires ink of which is low viscosity scale is of 0.001 – 0.05 Pa.s [1]. Possible printing layer thickness is in scale 0.05 – 20 µm [1]. Droplet size of ink and distance, ink surface tension and viscosity should be considered to achieve high quality printed pattern. Typically, conductive inks are made of metals containing copper or silver nanoparticles in order to achieve high electrical conductivity but also gold and aluminium are options. [1]

2.4 Substrates

Two of the sample structures were printed on Polyethylene terephthalate (PET) substrates. PET's characteristics are good heat resistance, electrical insulation capability, solvent resistance and price. In addition, it is flexible, light weight and recyclable. Dielectric constant is typically 3.0 @1 MHz, dielectric strength 60 kV/mm and volume resistivity 10^{16} Ω cm. [2] [3]

Polyimide (PI) substrate has high mechanical strength, it is thermally stable with good insulation characteristics. Furthermore, it is flexible as PET substrate. Dielectric constant is ~ 3.4@ 1MHz and dielectric strength 33 kV/mm and typical volume resistivity is 10^{18} Ω cm.
[2] [3]

Three substrate materials were used for studying signal behaviour in three dedicated signal frequencies 25, 35 and 45 MHz. Samples materials depicted in Table 1.

Table 1. Substrate Materials

Sample	Substrate type	Material	Ink
1.	PET	Kernowprint 135HWLD	Silver ink Asahi LS411AW
2.	PI	Kapton	Silver ink Asahi LS411AW
3.	PET	Autostat CT4	Silver ink Asahi LS411AW

Lay-out dimensional parameters were identical in all three samples as illustrated Figure 3.

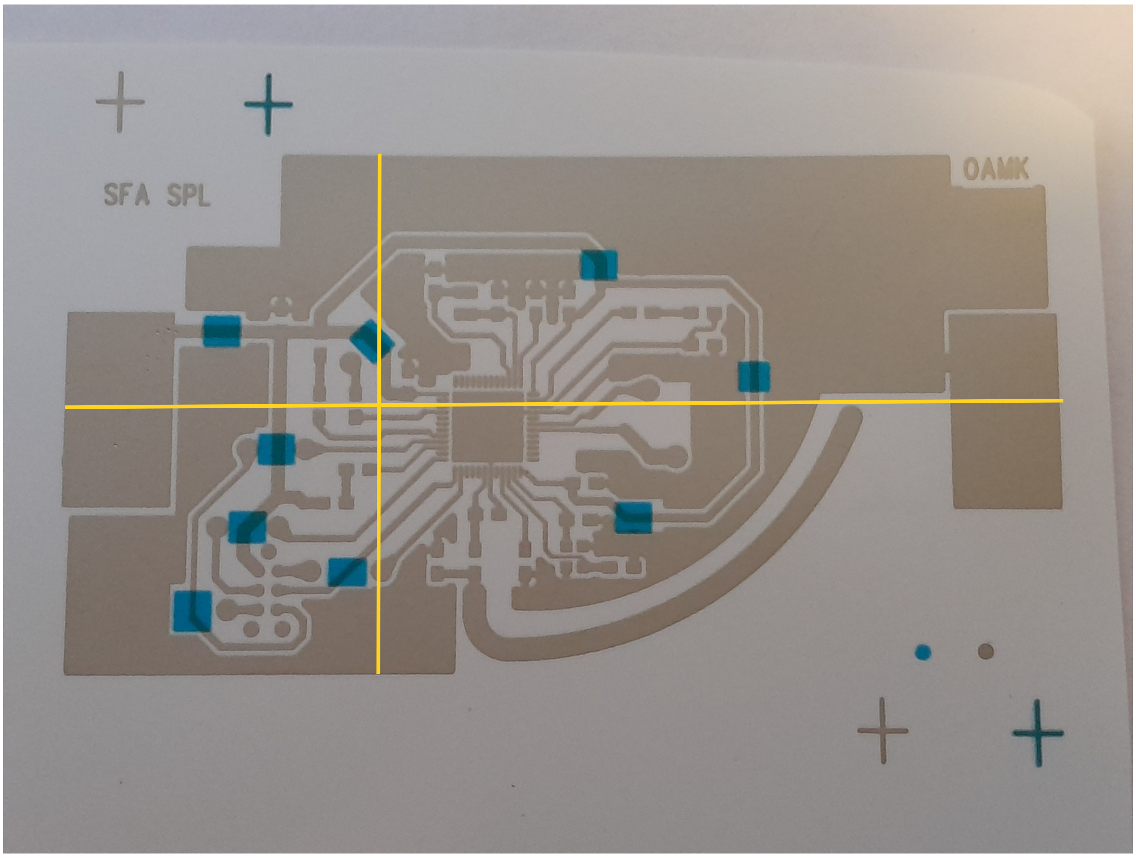


FIGURE 3. Lay-out printed on PET substrate. Dimension of structure were width 66 mm and height 35 mm.

2.5 Ink characteristics

Ink types can be divided in three main categories: conductive, semiconductive and dielectric materials. In general, Ink properties such as viscosity or clogging feature are modified by adding solvent which is removed after printing process when optimized properties are achieved. [5]

Silver ink contains Ag nanoparticles typically size of 1-100 nm and can be in different shapes e.g. nanospehers, cubes or nanowires. Among various nanoparticle materials, silver nanoparticles (Ag NPs) have gained an enormous relevance due to their high electrical conductivity, low cost with respect to gold, relative resistance to oxidation, and biocidal properties. Currently, silver-based inks are used in micro- or nano-electronic industries by printing technologies in a broad set of applications such as sensors, solar cells, thin-film transistors, or supercapacitors [5]

LS411AW is silver based ink and similar to copper, it is highly conductive. Silver ink sheet resistance is less than 40 $m\Omega\square^{-1}$ [10] and silver [Ag] nanoparticle concentration 65-75%.
LS411AW electrical performance has been studied by scholars and results indicate that this type of ink is suitable for fabricating complex structures such as flexible sensors [10]. In addition, earlier studies indicated that structures can endure environmental stress well.[5]

2.6 Sample substrate lay-out and electrical properties

Substrate electrical characteristics have impact on signal quality. Each substrate trace resistance were pre-measured with multimeter. Capacitance was estimated based on signal integrity measurement with oscilloscope and simulation modelling. There are two typical transmission line topologies: microstrip and stripline. In this thesis sample topology is microstrip, i.e., it has one transmission layer on surface of the substrate and top of it is not limited by other solid material such as dielectric. The other side is limited to dielectric material surface which are in this case PET and PI.

Table 2. Lay-out trace resistance of samples

Sample number	Substrate material	Trace Resistance A → B	Capacitance
1.	PET, kernowprint 135HWLD	7 Ω	40 pF
2.	PI, kapton	10 Ω	40 pF
3.	PET, Autostat CT4	17 Ω	40 pF

Measured trace length of samples from input A to output B measurement point was ~7.2 mm.

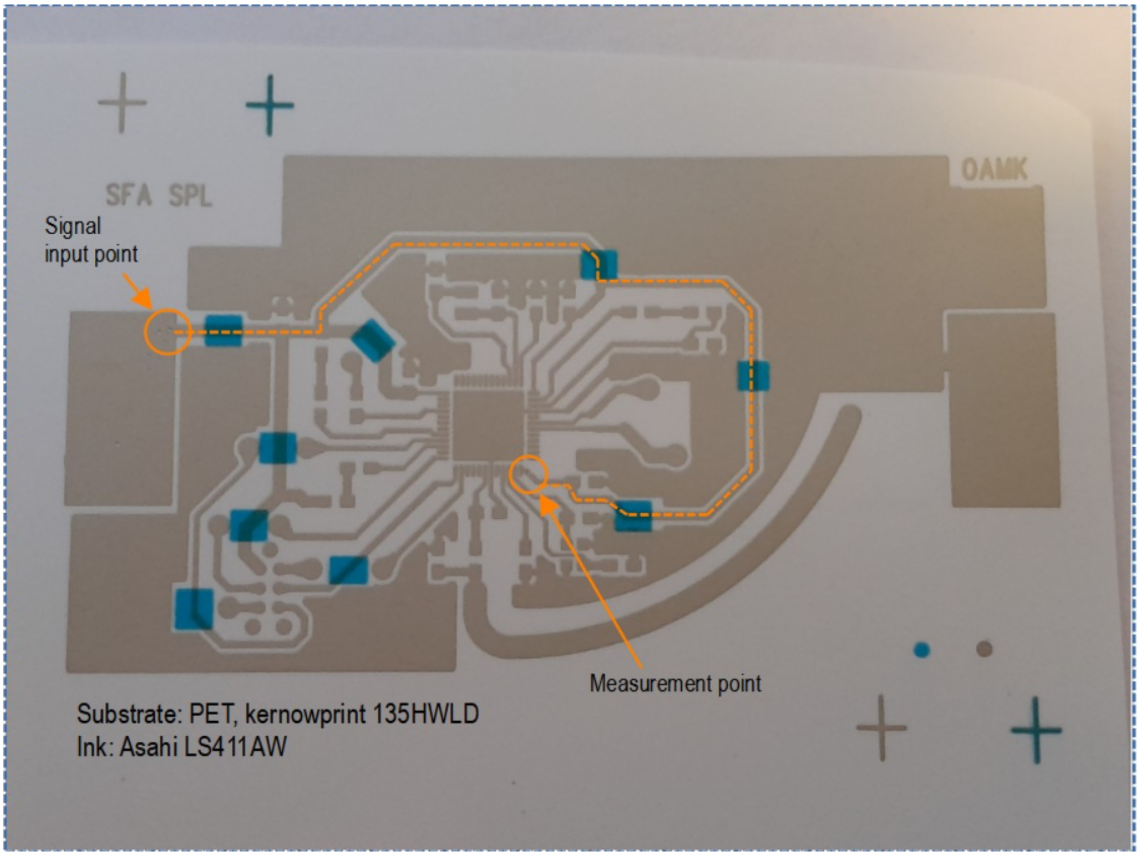


FIGURE 4. Sample 1. Substrate material PET, kernowprint 135HWLD

Kernowprint is flexible and waterproof material. It is resistant to various chemicals such as alcohol, acids, gas and oils. Material is heat tolerant, mechanically durable and can be used in indoor and outdoor applications thus making Kernowprint suitable substrate material for various FHE devices. In addition, PET is also low-cost material.[3] [11]

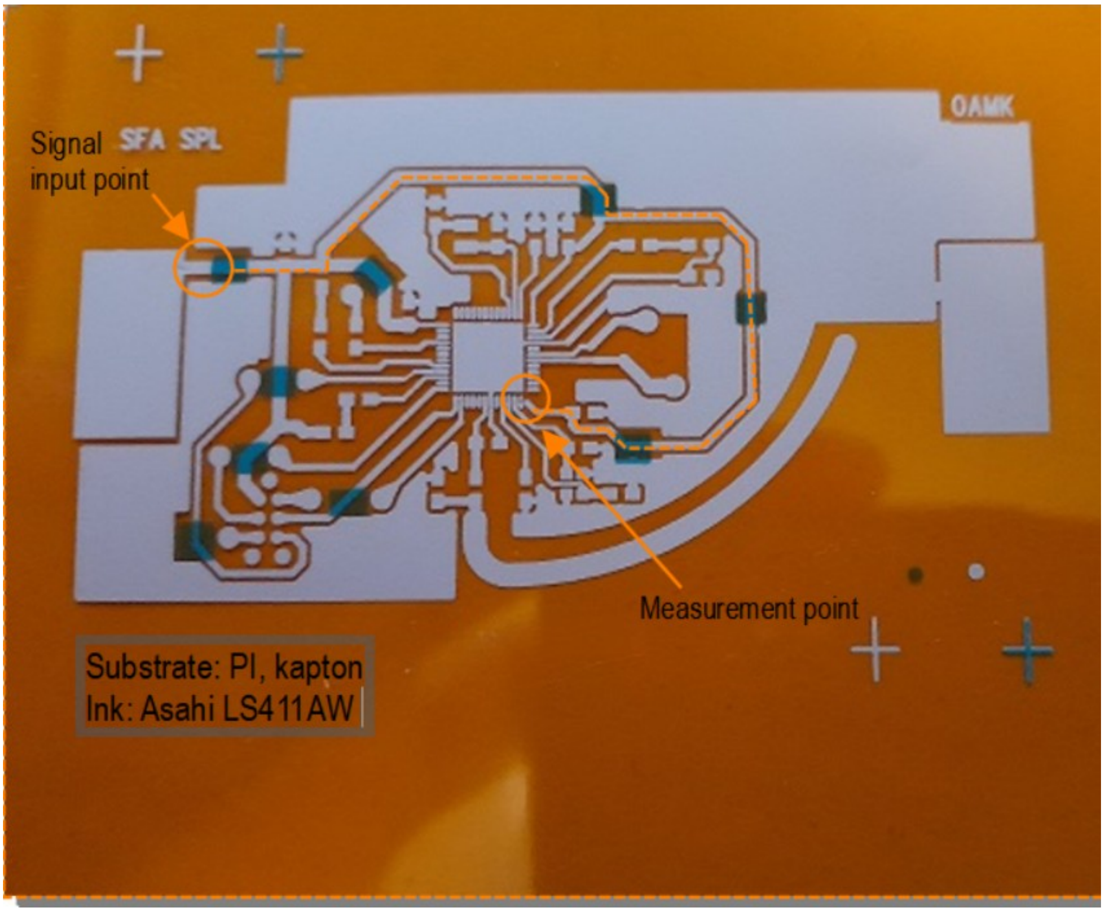


FIGURE 5. Sample 2. Substrate material PI

Kapton can withstand extremely high and low temperatures ranging from -269 to +400 °C maintaining mechanical and electrical properties. Furthermore, dielectric properties are good and provides electrical insulation at low temperatures. Kapton is flexible but has poor resistance to mechanical wearing and it is more expensive substrate material compared to PET. [3] [12]

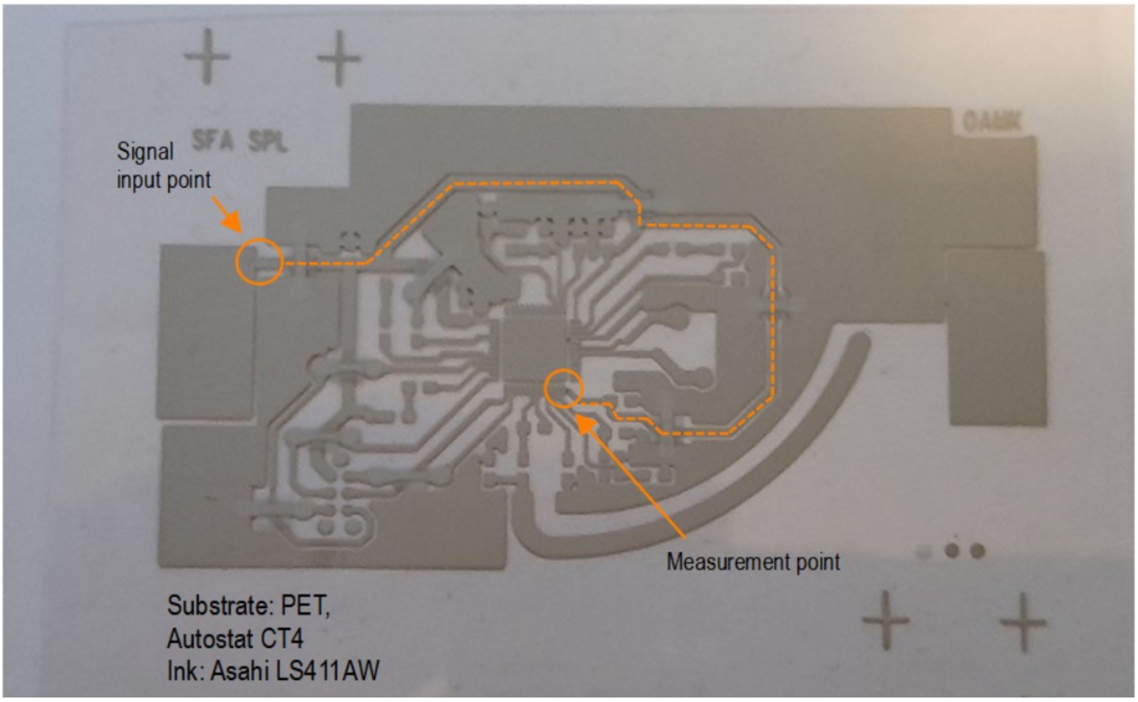


FIGURE 6. Substrate material PET Autostat CT4

Autostat film shrinkage is low at high temperatures so 150 °C is a suitable temperature for multiple printing operations. It is dimensionally stable and can be used as substrate material for various flexible solutions such as sensors and ID tags. [13]

3 SIGNAL THEORY BACKGROUND

All electrical circuit structures have some kind of capacitance that is, property to keep electrical charge for a time and then discharge electrical charge. This happens usually quickly in picoseconds depending on material and dimensions. In electrical circuits traces capacitance refers to self-capacitance or parasitic capacitance, i.e. holding charge between two parallel conductive traces or planes which are separated by dielectric material. Furthermore, trace resistance and impedance have an effect on signal between transmitter and receiver. Together these parameters acts as a RC- circuit on printed structure, in other words as a low pass filter. Generally, printed device dielectric constant should be low in order not to reduce quality of high-speed signals. For instance, output rise and fall times are combination of output impedance and capacitance. Furthermore, rise and fall time have impact on system design bandwidth requirement. [7]

3.1 Signal integrity

Signal integrity is in key role when high speed transmission reliability is assessed in order to ensure feasible circuit operation. Bit level error can cause functionality risk in form of application transmission failure. This may occur if, for example, signal levels are out of threshold range or it is heavily distorted. In this research, square wave clock signal was used for inserting to trace path three different frequencies, 25 MHz, 35 MHz and 45 MHz. Selected frequencies are described later in this study. Preliminary measurements showed that lower frequency rate such as 100 – 500 kHz indicates no signal degradation in these structures. Three substrates with the same printed microstrip structures were measured and studied.

Trace capacitance, resistance and length have an effect on transmission line as well as design layout. Trace height and width affects on resistance i.e. characteristic impedance as well as printed ink properties through conductivity. Line capacitance is depend on separation distance between two traces and microstrip dielectrics surrounds. Mutual capacitance is considered the ability to keep a charge between two adjacent conductors separated by a dielectric insulator similar to capacitor. In addition, higher frequency resulting to bigger reactance caused by the capacitance and can finally cause signal distortion and timing failure.

3.2 Transmission line

Transmission line is a conductive connection or signal route between digital transmitter and receiver. In addition, high-speed signal, even a very short trace, can exhibit transmission line effects between ICs as attenuation and signal distortion. [8]

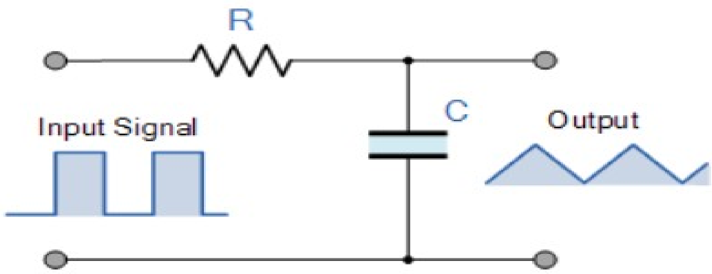


FIGURE 7. Simplified RC circuit schematic [6]

However, higher signal frequency leads to greater reactance caused by the capacitance and therefore greater signal loss occurs. Reactance value depend on frequency and capacitance according to equation 3.2.

Equation 3.2

$Xc = \frac{1}{2\pi * f * C}$ Xc= reactance f= frequency C= capacitance

Equation 3.3

Impedance Z in circuit:

$Z = \sqrt{R^2 + Xc^2}$

R= resistance

Xc= reactance

Equation 3.4

And Vout can be described as follows:

$$Vout = \frac{Vin * Xc}{Z}$$

Vout level calculation:

R= 17 Ω

Xc= 88 Ω

Vin= 3.2 V

$Vout$= 3.14 V

System total impedance in combination with capacitive reactance causes voltage level drop. Furthermore, as signal frequency increases more square wave frequency components are filtered out so that signal shape changes to sinusoidal form. Both effects are observed during measurements and illustrated later in this document.

4 MEASUREMENT

4.1 Measuring equipment

Multimeter 4 ¾ Digit Programmable HM8012 was used for resistance measurement. Test frequencies for evaluation were fed to substrate structures via Function Waveform Generator (Agilent 3325A). Actual measurements were took by 12 GHz oscilloscope (Infiniium DSA91204A Digital Signal Analyzer) and with 1 GHz active probe characteristics of 1pF input capacitance and 1 Mohm impedance.

4.2 Set-up and selected test frequencies

Preliminary measurements indicated that frequencies below MHz have no considerable effect on signal integrity. Based on this observation higher signal speeds were focused on. On the other hand, sample frequencies used for measurement were chosen based on commonly used application interfaces and clocking rates as illustrated in the table below. Usually, applications or devices have clocking system to operate.

Table 3. Frequency ranges and applications

Max. 25 MHz	Used for a universal asynchronous receiver-transmitter (UART) bus clocking. Accurate rate is 25.8 MHz. eMMC – memory clock rate 25 MHz
Max. 35 MHz	30.0 MHz Common CPU clock. Used in some ISM wireless systems 33.33 MHz Common CPU clock and used for Peripheral Component Interconnect (PCI) bus clock
Max. 45 MHz	38.4 MHz Common frequency for reference clock. Used as reference clock in some Bluetooth systems. 40.0 MHz Common CPU clock, WiFi, OFDM, Used in some WiFi, Bluetooth and BLE, RFID/NFC, SimpleLink system

4.3 Measurement and analysis

Signal integrity study process proceeded taking first reference measurement on initial input signal waveform. After this, pulse pattern was entered to input point of sample lay-out and measured at the end of signal transmission path. Reference signal depicted in figure 4.

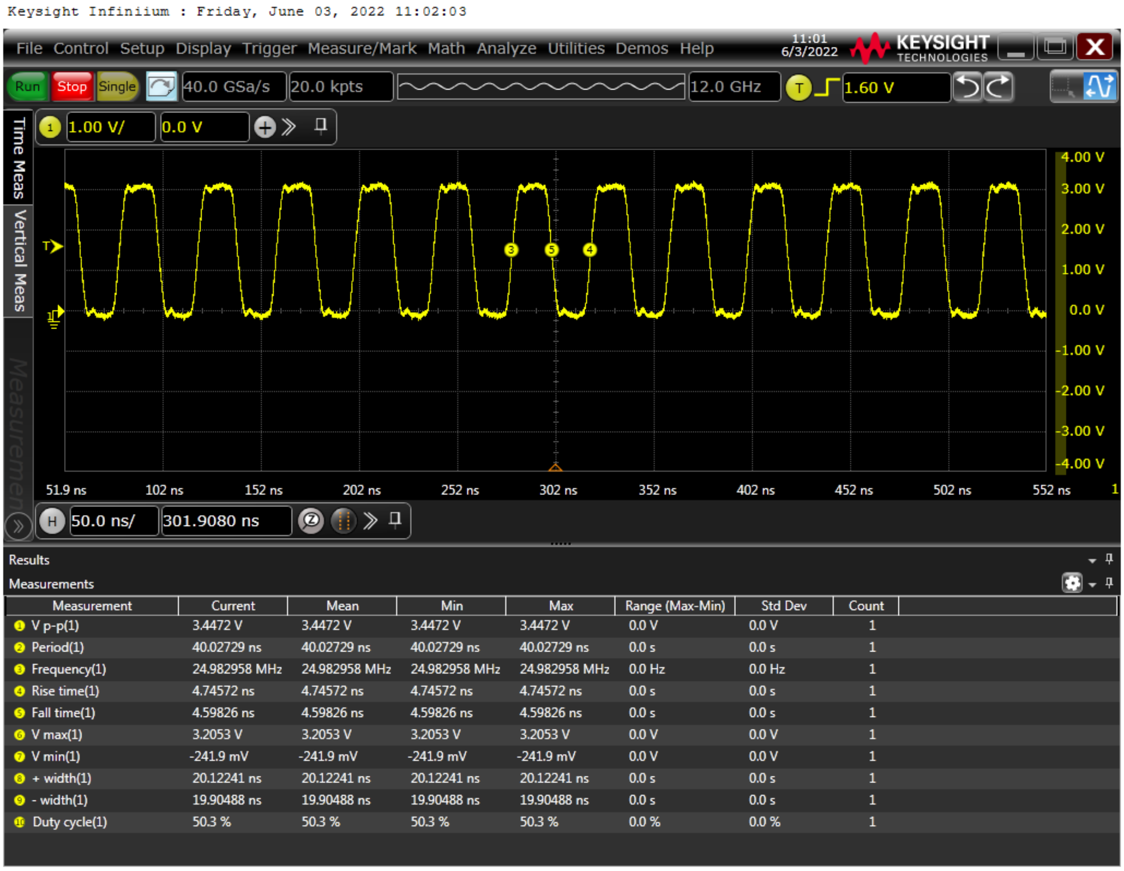


FIGURE 8. Reference signal @ 25 MHz. Reference signal was measured directly from signal generator output with oscilloscope.

25 MHz output measurement results illustrated in following figures.

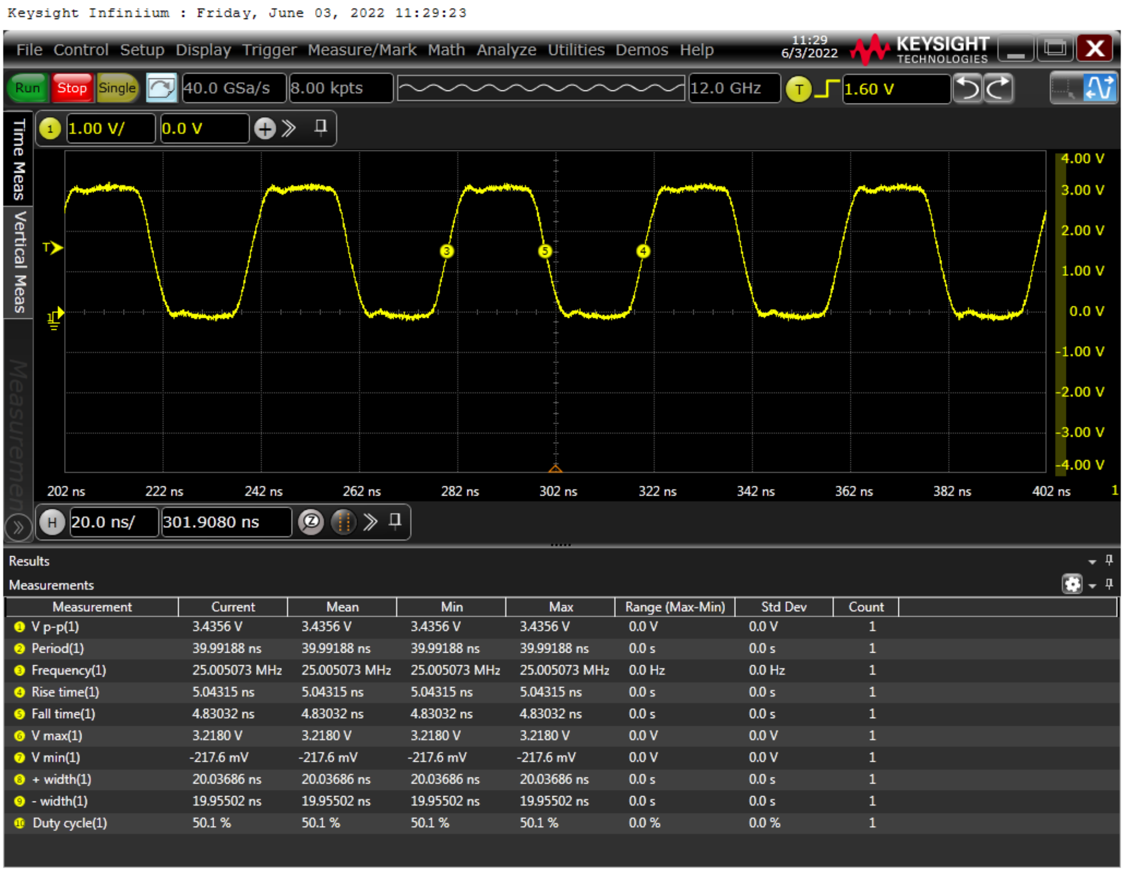
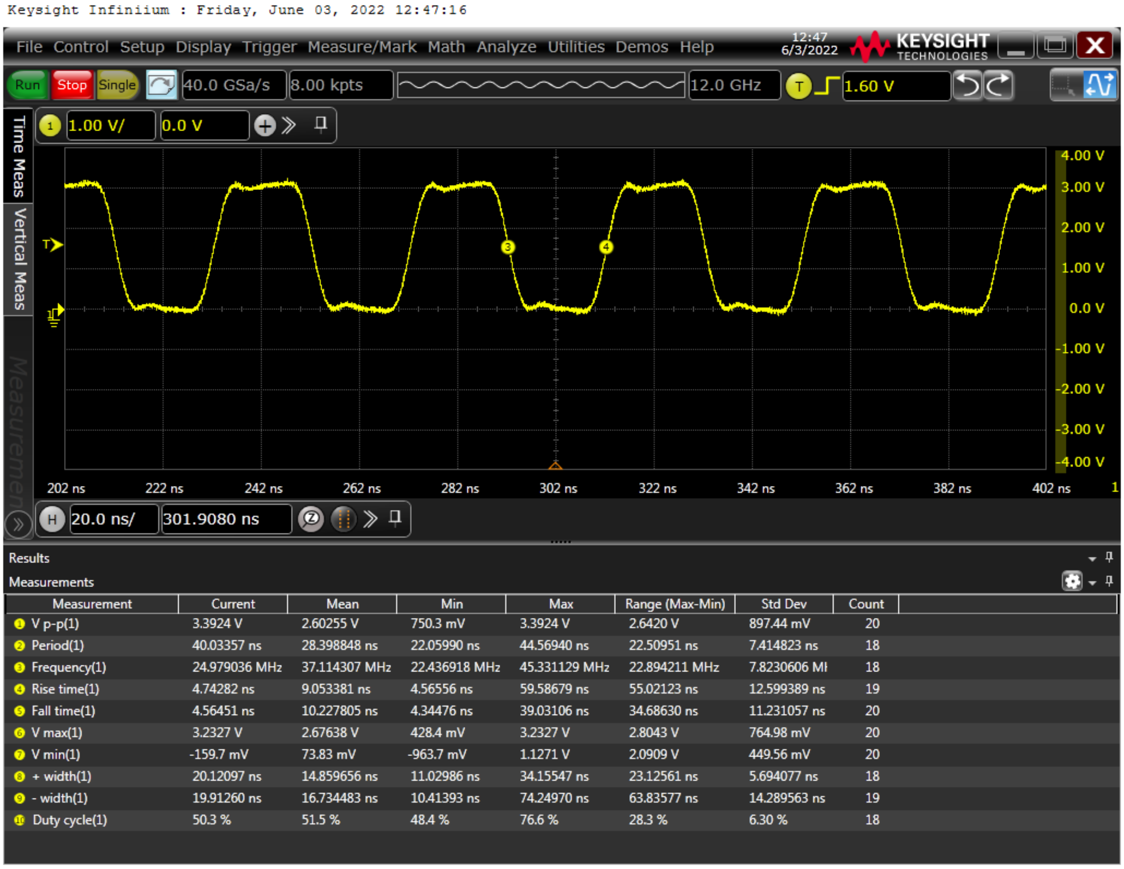


FIGURE 9. Sample 1. Output signal @ 25 MHz Kernowprint 135HWLD



Measurement	Current	Mean	Min	Max	Range (Max-Min)	Std Dev	Count
V p-p(1)	3.3924 V	2.60255 V	750.3 mV	3.3924 V	2.6420 V	897.44 mV	20
Period(1)	40.03357 ns	28.398848 ns	22.05990 ns	44.56940 ns	22.50951 ns	7.414823 ns	18
Frequency(1)	24.979036 MHz	37.114307 MHz	22.436918 MHz	45.331129 MHz	22.894211 MHz	7.8230606 MI	18
Rise time(1)	4.74282 ns	9.053381 ns	4.56556 ns	59.58679 ns	55.02123 ns	12.599389 ns	19
Fall time(1)	4.56451 ns	10.227805 ns	4.34476 ns	39.03106 ns	34.68630 ns	11.231057 ns	20
V max(1)	3.2327 V	2.67638 V	428.4 mV	3.2327 V	2.8043 V	764.98 mV	20
V min(1)	-159.7 mV	73.83 mV	-963.7 mV	1.1271 V	2.0909 V	449.56 mV	20
+ width(1)	20.12097 ns	14.859656 ns	11.02986 ns	34.15547 ns	23.12561 ns	5.694077 ns	18
- width(1)	19.91260 ns	16.734483 ns	10.41393 ns	74.24970 ns	63.83577 ns	14.289563 ns	19
Duty cycle(1)	50.3 %	51.5 %	48.4 %	76.6 %	28.3 %	6.30 %	18

FIGURE 10. Sample 2. Output signal @ 25 MHz PI, kapton

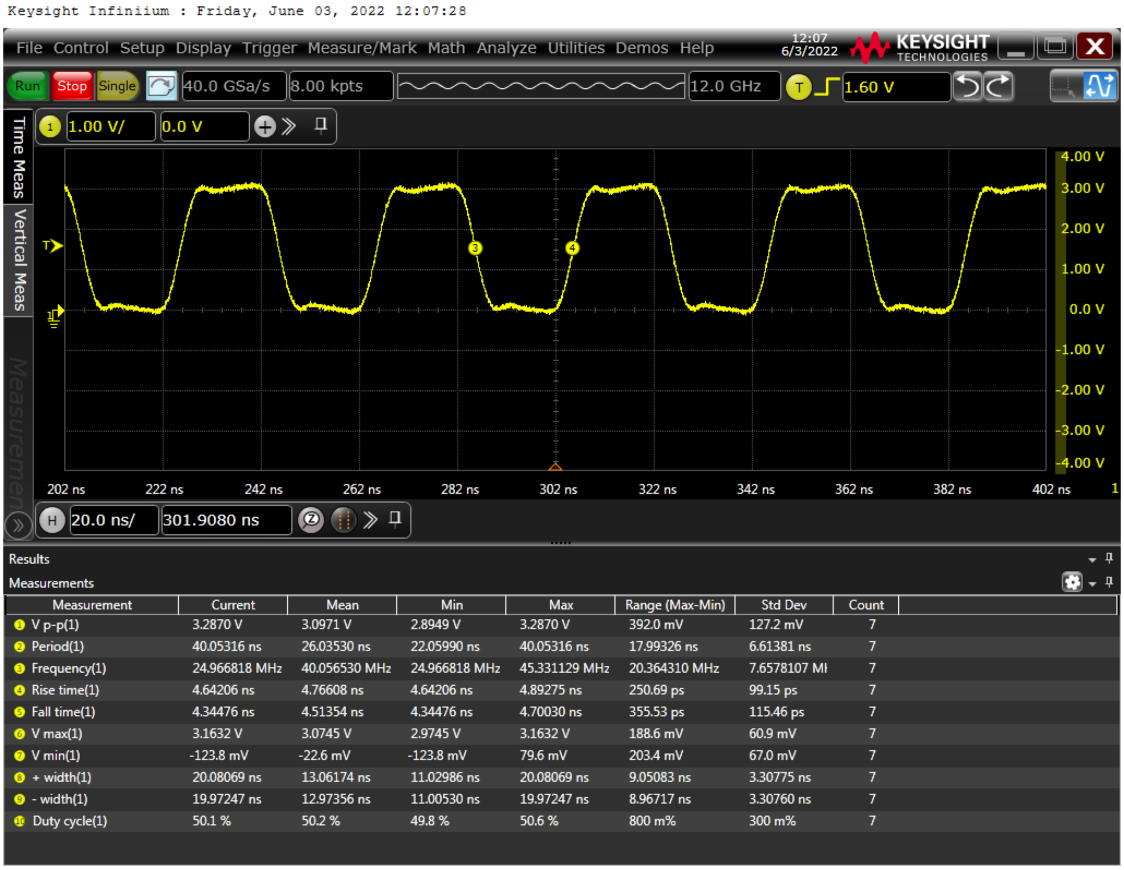
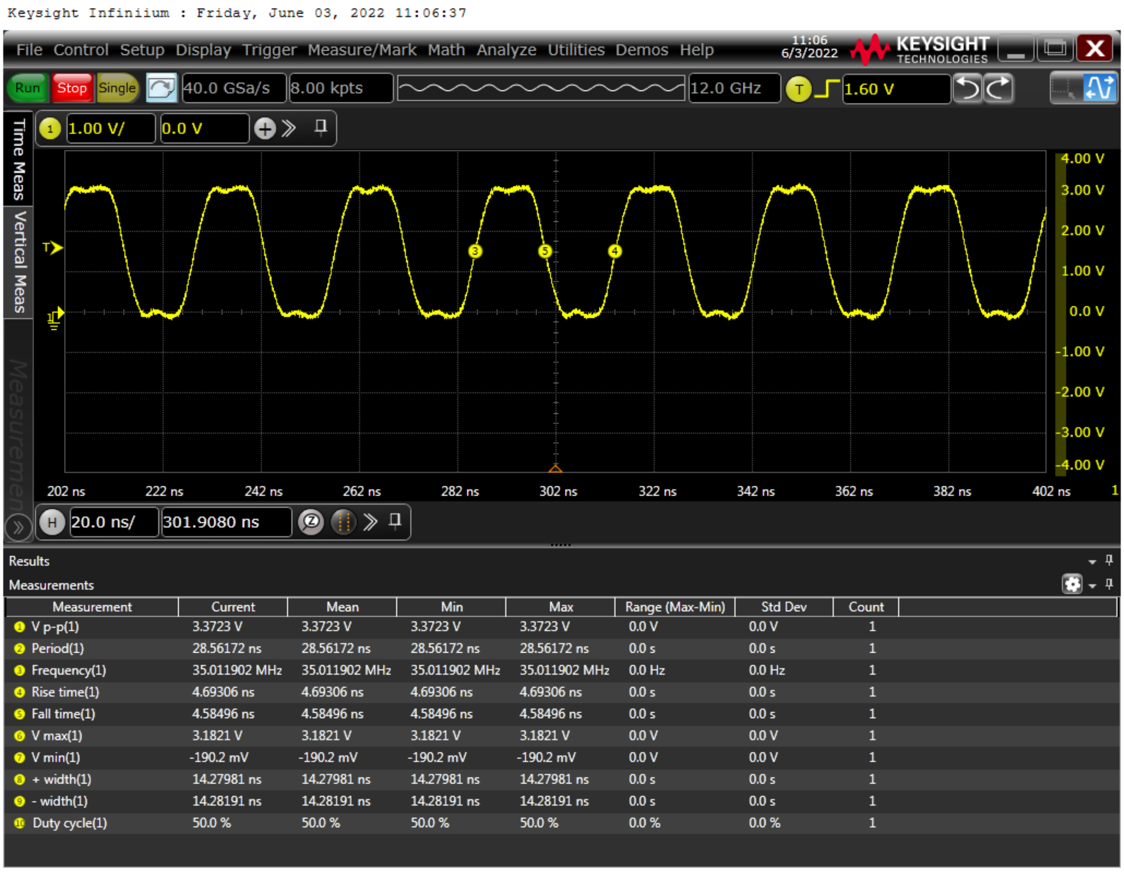


FIGURE 11. Sample 3. Output signal @ 25 MHz PET, Autostat CT4

Waveform has sharp rising and falling edges and shape is close to reference input signal.

35 MHz output measurement results illustrated in following figures.



Measurement	Current	Mean	Min	Max	Range (Max-Min)	Std Dev	Count
V p-p(1)	3.3723 V	3.3723 V	3.3723 V	3.3723 V	0.0 V	0.0 V	1
Period(1)	28.56172 ns	28.56172 ns	28.56172 ns	28.56172 ns	0.0 s	0.0 s	1
Frequency(1)	35.011902 MHz	35.011902 MHz	35.011902 MHz	35.011902 MHz	0.0 Hz	0.0 Hz	1
Rise time(1)	4.69306 ns	4.69306 ns	4.69306 ns	4.69306 ns	0.0 s	0.0 s	1
Fall time(1)	4.58496 ns	4.58496 ns	4.58496 ns	4.58496 ns	0.0 s	0.0 s	1
V max(1)	3.1821 V	3.1821 V	3.1821 V	3.1821 V	0.0 V	0.0 V	1
V min(1)	-190.2 mV	-190.2 mV	-190.2 mV	-190.2 mV	0.0 V	0.0 V	1
+ width(1)	14.27981 ns	14.27981 ns	14.27981 ns	14.27981 ns	0.0 s	0.0 s	1
- width(1)	14.28191 ns	14.28191 ns	14.28191 ns	14.28191 ns	0.0 s	0.0 s	1
Duty cycle(1)	50.0 %	50.0 %	50.0 %	50.0 %	0.0 %	0.0 %	1

FIGURE 12. Reference signal @ 35 MHz.

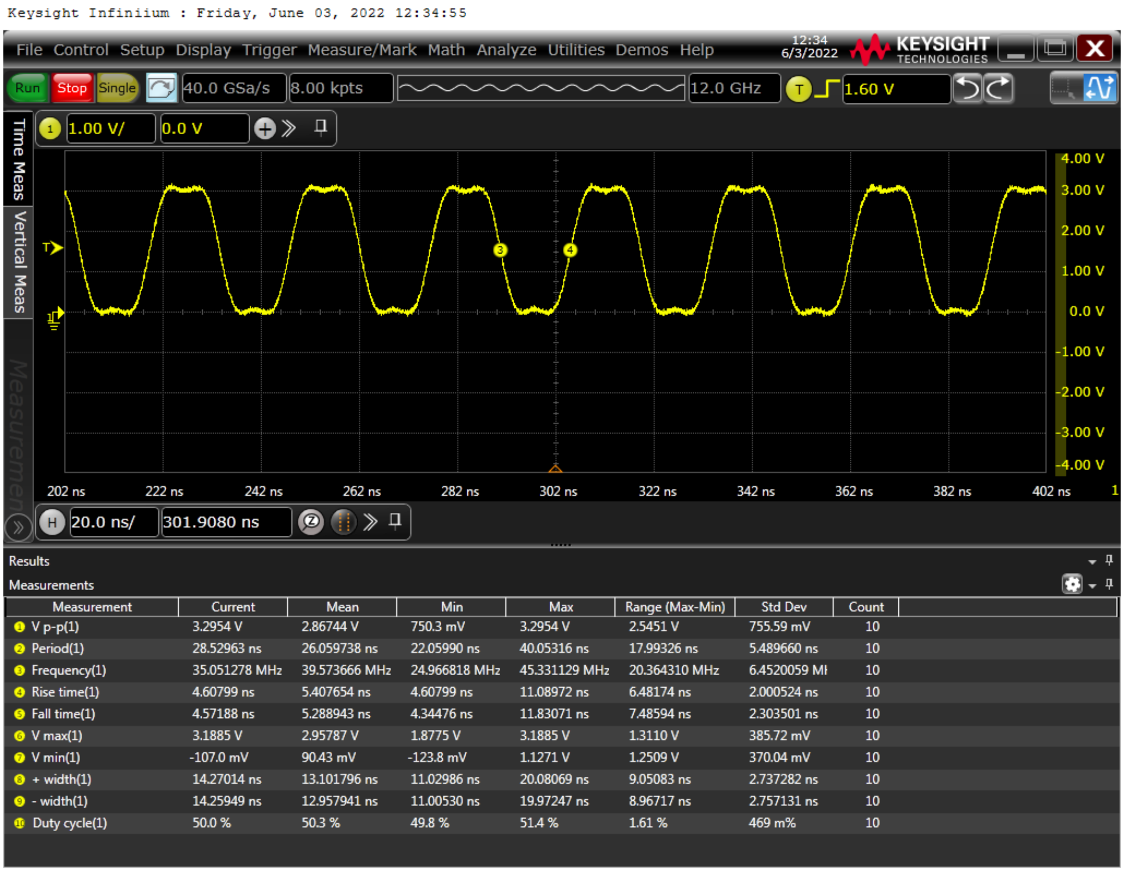


FIGURE 12. Sample 1. Output signal @ 35 MHz PET, kernowprint 135HWLD

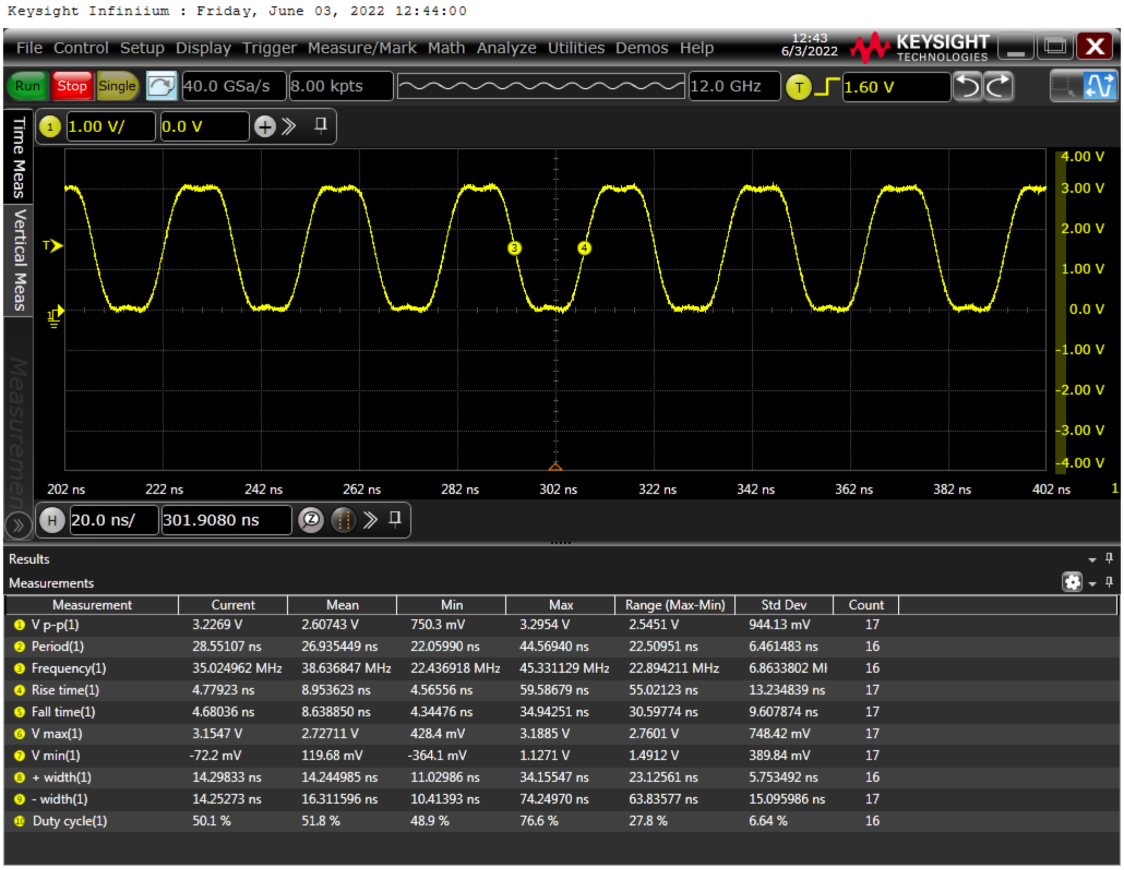


FIGURE 13. Sample 2. Output signal @ 35 MHz PI, kapton

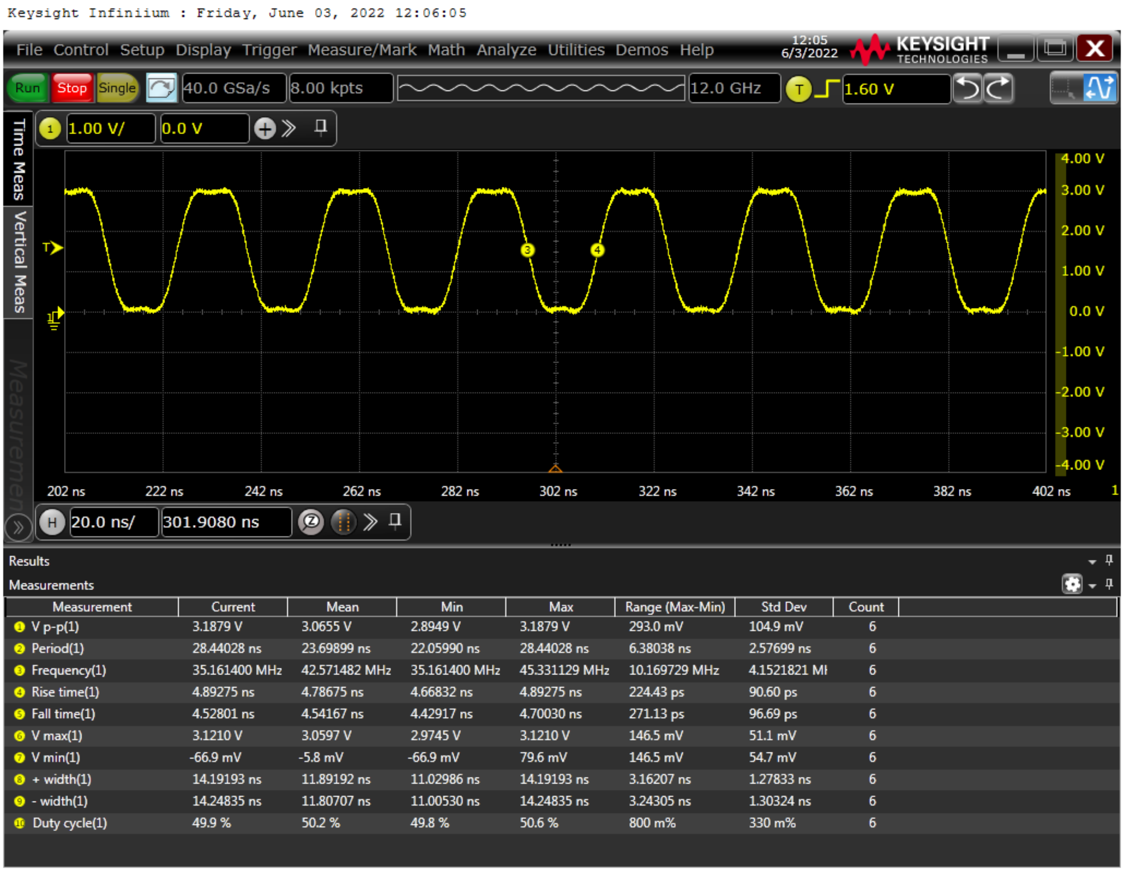


FIGURE 14. Sample 3. Output signal @ 35 MHz PET, Autostat CT4

No major signal distortion occurred at 35 MHz in any sample designs. Rising and falling edges were steep and waveform was coherent.

45 MHz output measurement results are illustrated in the following figures.

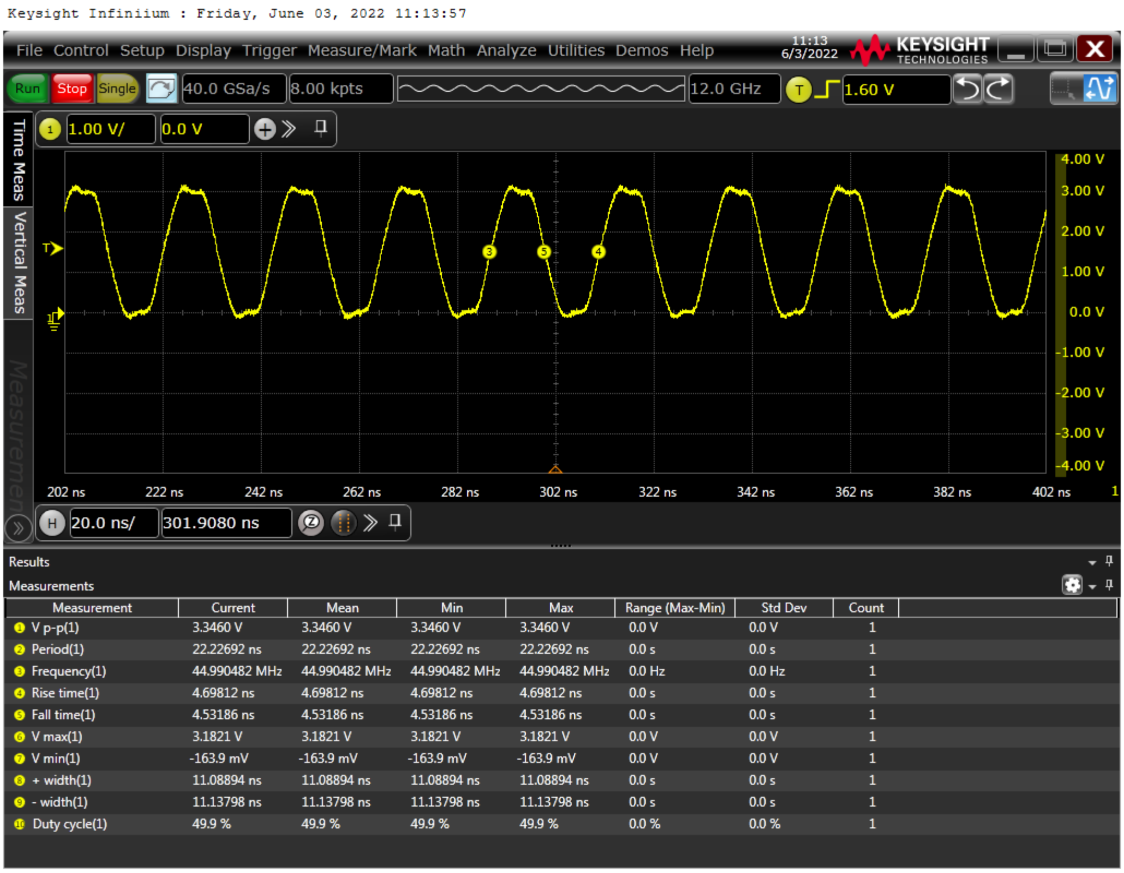


FIGURE 15. Reference signal @ 45MHz without substrates.

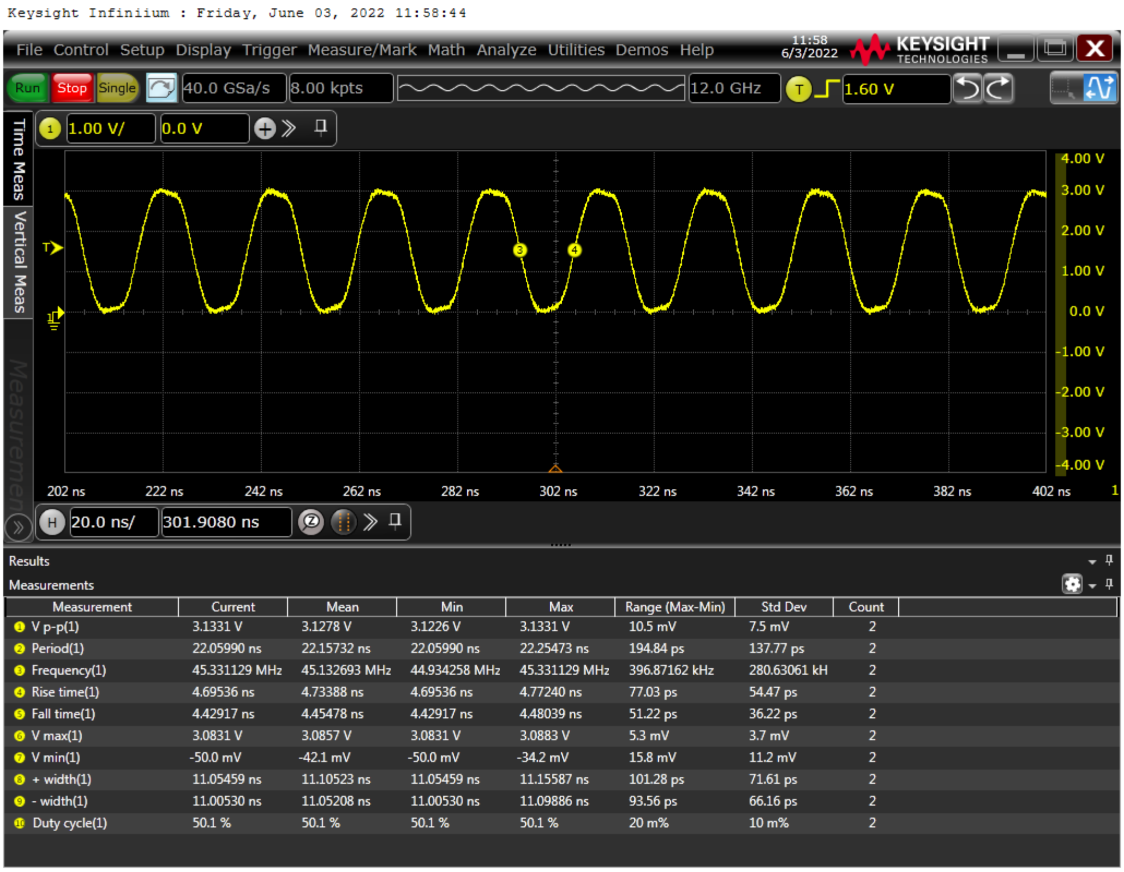


FIGURE 16. Sample 1. Output signal @ 45 MHz PET, kernowprint 135WLD

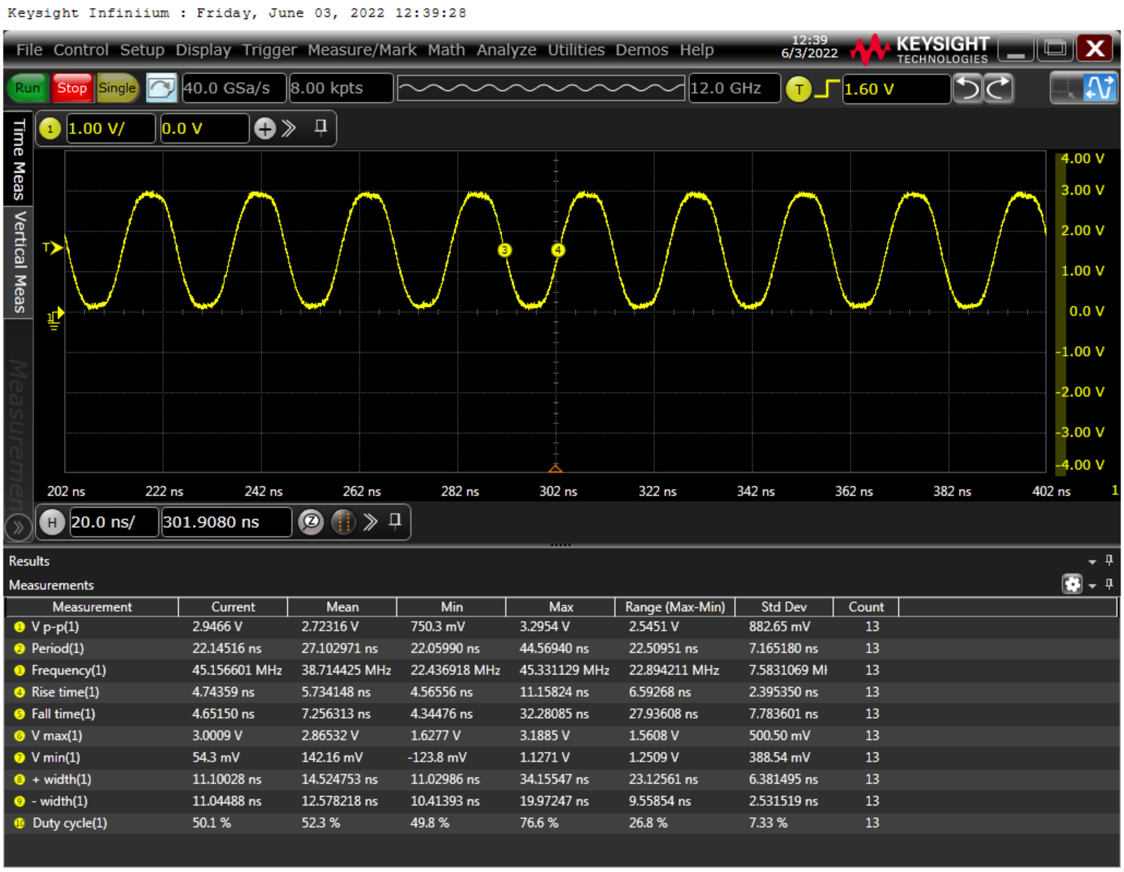


FIGURE 17. Sample 2. Output signal @ 45 MHz PI, kapton

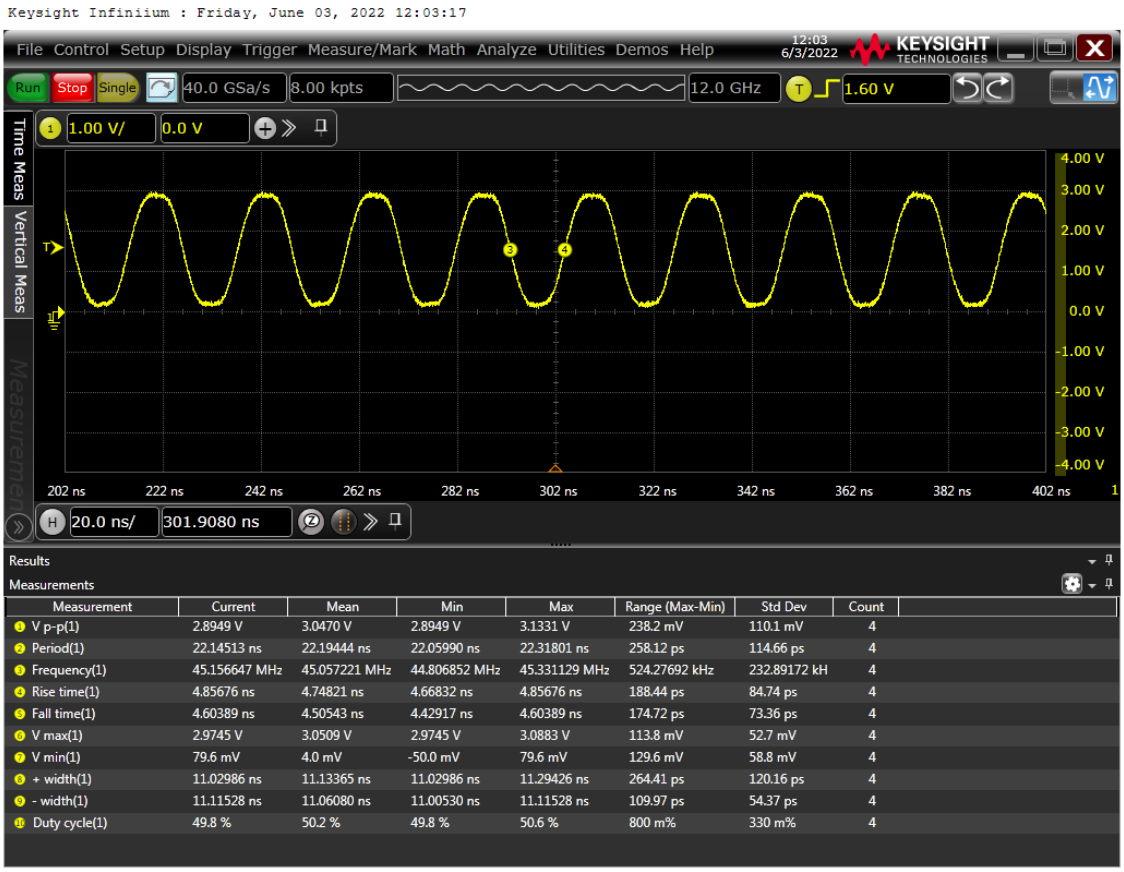


FIGURE 18. Sample 3. Output signal @ 45 MHz PET, Autostat CT4

At 45 MHz signal shape began to reshape towards sinusoidal waveform. Also voltage high level was decreased slightly.

4.4 Waveform result analysis

5 key parameters were selected for analysis basis, illustrated in tables 4,5 and 6,

Table 4. 25 MHz rate result

Parameter @ 25 MHz	**Reference**	Sample 1 [PET]	Sample 2 [PI]	Sample 3 [PET]	Unit
V max	**3.2**	3.2	3.2	3.2	V
V p-p	**3.4**	3.4	3.4	3.4	V
Rise time	**4.7**	4.7	4.7	4.6	ns
Fall time	**4.6**	4.5	4.6	4.3	ns

Duty cycle	**50.3**	50.3	50.3	50.1	

25 MHz signal waveform shape and voltage levels remained close to original reference signal as seen in results in table 4.

Trace resistance and capacitance had only slight effect on signal quality. Minor change was seen in rise and fall time with Sample 3 [PET] thus differences can be partially considered to be within measurement tolerance. Typical measurement error when measuring rise or fall times can expected to be approximately 2-3% depending on oscilloscope and probe combination. In case of sample 3 fall time deviation was ~ 6% compared to reference signal. V max and peak-to-peak values were at the same level and no reduction occurred between samples, also duty cycle was stable and no notable deviation was observed.

Table 5. 35 MHz rate result

Parameter @ 35 MHz	**Reference**	Sample 1 [PET]	Sample 2 [PI]	Sample 3 [PET]	Unit
V max	**3.2**	3.2	3.2	3.1	V
V p-p	**3.4**	3.3	3.2	3.2	V
Rise time	**4.7**	4.6	4.8	4.9	ns
Fall time	**4.6**	4.5	4.7	4.5	ns
Duty cycle	**50.0**	50.0	50.1	50.1	%

At 35 MHz signal rate shows V p-p began to decline in all samples due to reactance increase according to higher input frequency . Same effect was seen also in Sample 3 with V max and its rise time was increased by 0.2 picoseconds.

Table 6. 45 MHz result

Parameter @ 45 MHz	**Reference**	Sample 1 [PET]	Sample 2 [PI]	Sample 3 [PET]	Unit
V max	**3.2**	3.2	3.0	3.0	V
V p-p	**3.3**	3.1	2.9	2.9	V
Rise time	**4.7**	4.6	4.8	4.9	ns
Fall time	**4.6**	4.5	4.7	4.5	ns
Duty cycle	**49.9**	50.1	50.1	49.8	%

45 MHz signal rate clearly caused V max drop in Samples 2 and 3. since both had higher trace resistance: Sample 2,10 Ohm and Sample 3. 17 Ohm. Consequently, voltage level dropped in these more resistive structures as illustrated in section 3.1 Transmission line and in Equation 3.4. Rise and fall times were not significantly affected compared with 35 MHz input frequency.

Most distorted signal was observed in sample 3 at 45 MHz frequency.

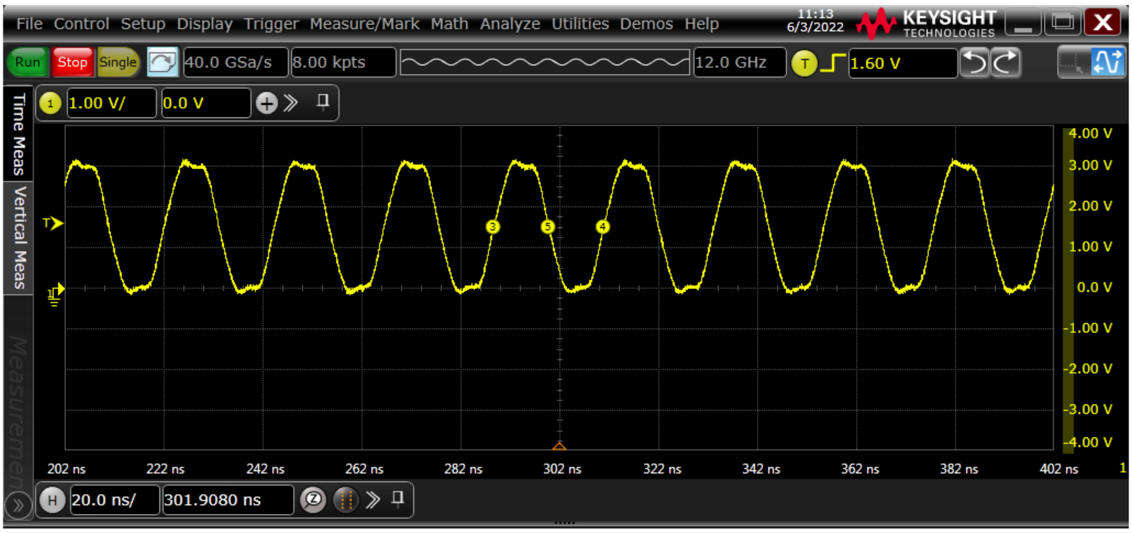


FIGURE 19. Sample 3, PET Autostat Silver ink Asahi LS411AW 45 MHz reference signal.

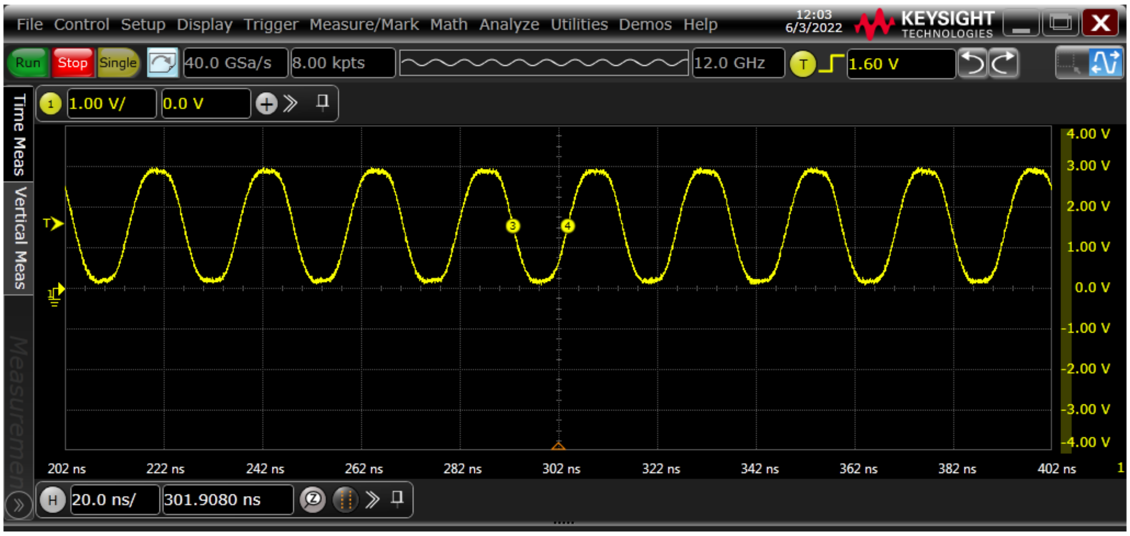


FIGURE 20. Sample 3, PET Autostat Silver ink Asahi LS411AW 45 MHz measured signal.

Resistance of sample 3 was 17 Ohm and other impacting electrical characteristics caused signal distortion as input frequency increases. Notable observation was that circuit parameters acted as low pass filter and filtered out the fastest signal components.

5 SIMULATION

Measurement results were simulated in order to study how increased frequency rate impacted on signal integrity in simulation modelling and compare those to real-time results. There were differences between real-time measurement and simulation model. In simulation model ground connection was ideal but in laboratory measurement non-ideal. This variation affected on results as non-ideal ground loop caused greater attenuation in signal voltage level and signal form decline.

5.1 Application

LTspice made possible to schematic capture and to enter an electronic schematic for an electronic circuit. A waveform viewer was used for showing simulation results. Ltspice design tool allowed to simulate and analyse electronic characteristic of circuit traces. Analysis was based on factors such as transient, noise and DC transfer function. Simulation model was performed and results are plotted graphically. [9]
Model was designed in order to study electrical parameters impact on each design sample results. Adjustable pulse generator model was made and used for square wave signal source. Voltage level, rise and fall times and frequency was set accordingly to real-time measurement where signal generator was used as a signal source.

5.2 Trace modelling

Parameter V1 is model of input signal and R1 for trace impedance of each sample. C1 is modelling total trace capacitance. R2 is10 MΩ signal route termination. Pulse generator V1 value was changed by 10 MHz scale from 25 MHz to 45 MHz and resistor R1 value was adjusted according to circuit signal trace resistance shown in table 2. Vout was the measuring point for output signal.

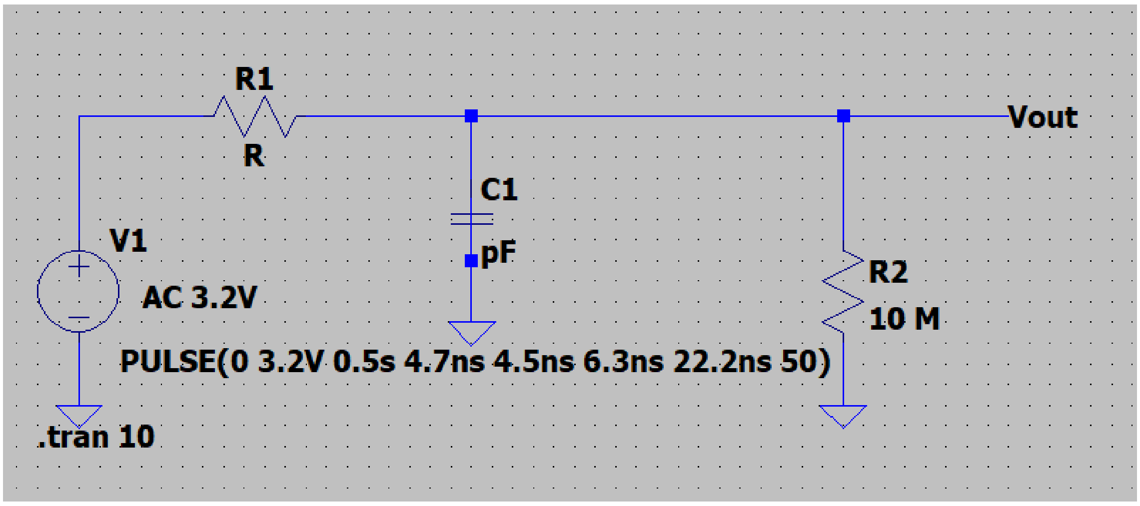


FIGURE 21. Simplified trace model

5.3 Analysis and comparison

Reference signal for input was created applying minor values for R1 and C1. As seen in figure 21. output signal fidelity is good due to small trace resistance and capacitance. This model represents input signal in real time measurement. Square wave frequency was adjusted to 45 MHz.

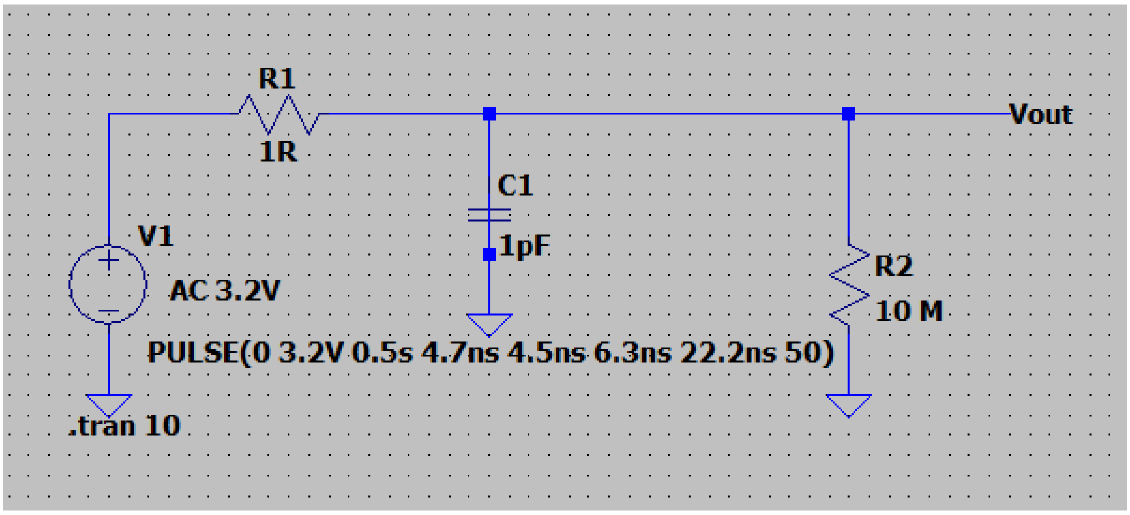


FIGURE 22. Ideal square wave source and trace model

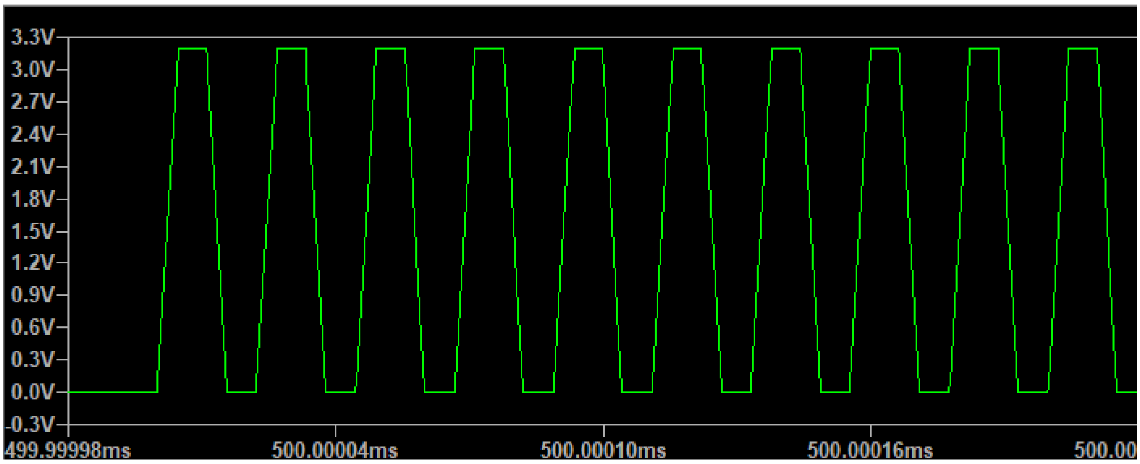


FIGURE 23. Ideal signal model output at 45 MHz

Square wave is an infinite series of sine wave harmonics added together. Square wave consists of multiple sine waves of different frequencies and all these were presented in this signal. Output signal rising and falling edges were steep and integrity of signal was good.

Trace resistance R1 was increased to 17 Ohm and capacitance C1 to 40 pF frequency was kept at 45 MHz rate and other parameters were left unchanged.

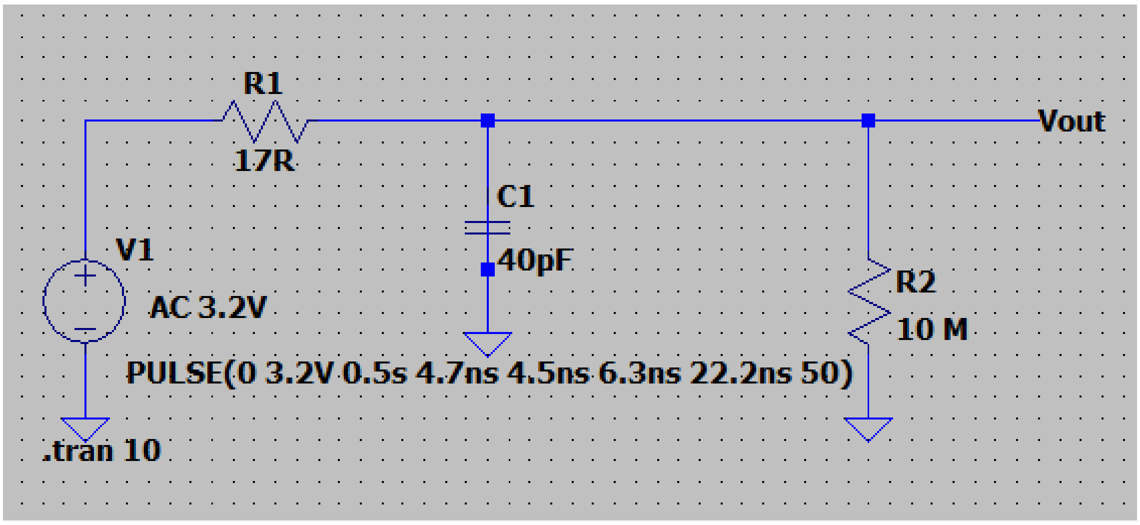


FIGURE 24. Trace resistance and capacitance added to model.

After simulation was executed with changed parameters signal changing towards sinusoidal shape due to resistance together with capacitance started to act as low-pass filter and filtering out sine wave components.

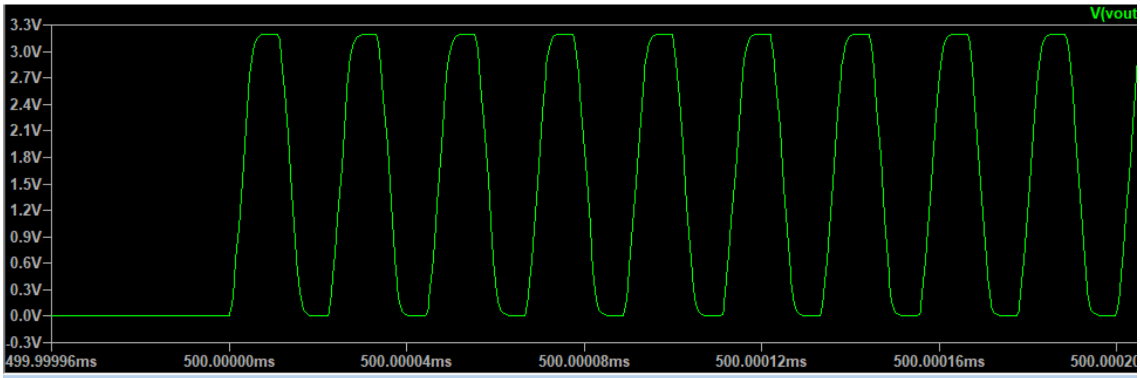


FIGURE 25. Trace resistance (impedance) and capacitance impact on signal shape.

Line resistance was set to 17 Ohm and capacitance to 40 pF and evolving digital degradation can be seen in Vout. This result correlated with real time measurements although signal high level decrease was less than in live signal. This phenomenon can be considered caused by grounding and/or current flow which were not taken in account by simulation model.

6 DISCUSSION

Expectations were that signals are distorted in some degree as frequency rate increases. Such impacts observed typically are signal level attenuation, overshoot and undershoot and ringing as frequency increases. These phenomena are typical also for electronics manufactured conventionally. Also, definition of parameters which have impact on signal quality and can be measured on substrate trace were in focus of this thesis. Simulation model was created for comparison and analysis for real-time measurement with a simulation model. Further development could include Fourier analysis concerning on signal behaviour and measuring higher signal frequencies.

Outside of thesis scope were left those electrical parameters which are assumed to have only a minor effect on signal integrity in this case study. Silicon based technology components have advantage in performance in computation i.e. robustness in switching rate and transmission speed. Folded microstrips have a great potential for next generation of hybrid electronics and opens new possibilities for bendable applications in small and large size. PE’s or FHE’s value chain is one of the key factors when considering applications for large-scale manufacturing.

7 CONCLUSION

Study results indicated that frequencies 25 – 45 MHz did not cause major signal distortion in sample circuits. On the other hand, square wave turned into sinusoidal shape but probability of bit error in case of data transmission was small due to rising and falling edges were continuous. Possibility to bit error could have been increased if rising edge would have non-continuous points, signal ringing or noise.

High speed signal transmitted along trace tends to attenuate. Attenuation is caused by capacitance between trace and other surrounding planes with dielectric constant together trace resistance. Notable is that signal trace length and other lay-out dimensional properties have a significant impact on signal quality. In this case the evaluated trace length was ~7.2 mm and lay-out surface area ~ 2300 mm^2. Especially due to short trace length signal notable degradation was observed only at 45 MHz range.

Results demonstrated that applications integrating conventional electronics to PE are feasible to implement when 25 MHz or higher signalling frequencies are involved.
Thus, silver ink enables good electrical characteristics for printed structures at least tens of MHz range due to its high conductivity. For instance, applications using 38.4 MHz reference clocking such as WiFi, Bluetooth and NFC solutions are feasible to print with silver ink. High speed frequencies rates are essential for devices which uses microcontroller, small CPU chip and memory module for data processing purposes.

Results of this study indicated that specimen involved had material and design characteristics to maintain moderate signal quality even with highest signal rate used in this study. In future measurements could be taken at higher signal frequencies with components assembled on printed structure.

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APPENDIX 1:

Characteristics of different printing methods [1]

	Gravure	Offset	Flexography	Screen	Inkjet
Throughput (m^2/s)	3–60	3–30	3–30	2–3	0.01–0.5
Resolution (lines/cm)	20–400	100–200	60	50	60–250
Printing speed (m/min)	100–1000	100–900	100–700	10–15	15–500

Material parameters of LS411AW silver ink and comparison [4]

Ink Manufacturer	Ag [%]	Solvent	Viscosity [cP]	Sheet resistance [m$\Omega\square^{-1}$@thickness]
CRSN2442 SunChemical	69–71	propylene diacetate	2000–3000	10@25µm
5064H DuPont	63–66	C11-ketone	10,000–20,000	<14@25µm
LS411AW Asahi	65–75	butyl cellosolve acetate, isophorone	20,000–30,000	<40@10µm
HPS-FG32 Novacentrix	75	butyl carbitol	8000	25@25µm
HPS-021LV Novacentrix	75	water	2600	≤14@25µm