Some discrete design signal conditioning options for SiPMs and other light sensors

David Fink, Sense School Meeting, Ringberg

Comparison of typical light sensor electrical characteristics (capacitance in particular):

Detector Type	Terminal Capacitance	Electronics Output Signal Rise Time
Fast Si Photodiode	0.5 pF	38 ps
1” PMT	~5 pF	1.5 ns
HPD	~5 pF (avalanche photodiode)	1.5 ns
6x6mm SiPM	1300 pF (Hamamatsu S13360-6050)	2.5 ns

- In general, larger capacitance means slower response times
- In particular, SiPMs with a large number of cells have significant terminal capacitance
- A comparison of different discrete approaches for implementing discrete component signal conditioning with emphasis on “fast” SiPM signals follows

Circuit Architectures: Simple 50 ohm resistor

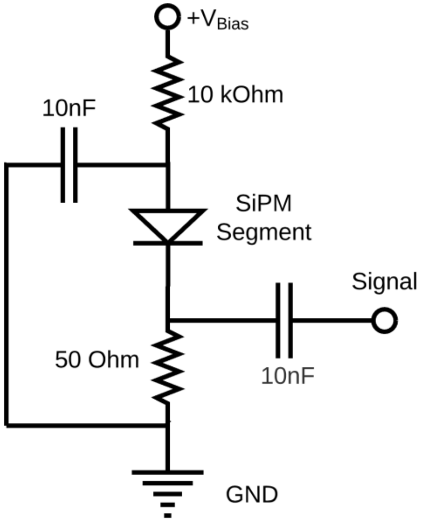
Can be simply implemented even with a piece of leftover PCB

Advantages

- Direct interface to 50 ohm interconnect
- Low power consumption (only passive components)
- Can be DC coupled

Disadvantages

- Fixed (no) gain
- Relatively high input impedance (50Ω)



In general, this is a good place to start and a place to come back to if you don‘t understand what some other fancy input circuit is doing

Circuit Architectures: MMIC amplifier

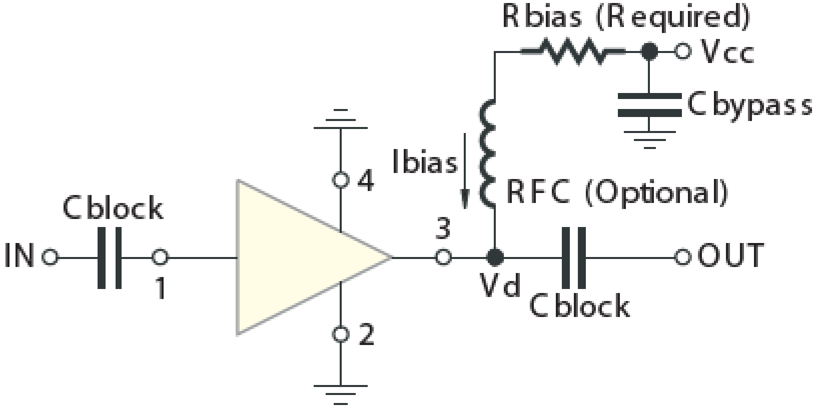
Requires implementation using proper RF design techniques – or purchase as a module

Advantages

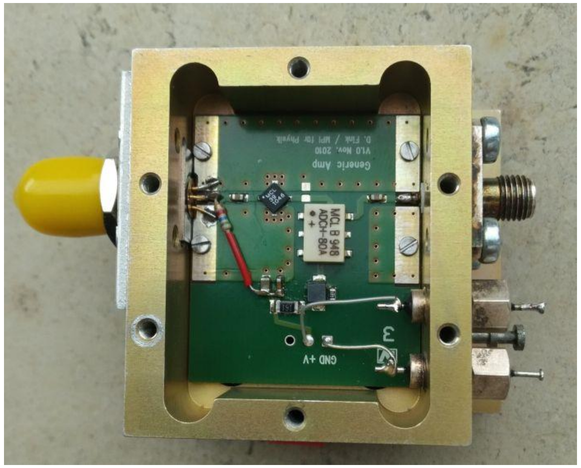
- High Bandwidth (>1 GHz)
- Low Noise compared to operational amplifier input stages
- Direct interface to 50 ohm interconnect

Disadvantages

- Fixed gain (~ 20 dB typical)
- Relatively high input impedance (50Ω)
- Current consumption (40 mA per device)
- AC coupled (separate monitor needed for DC current readout)

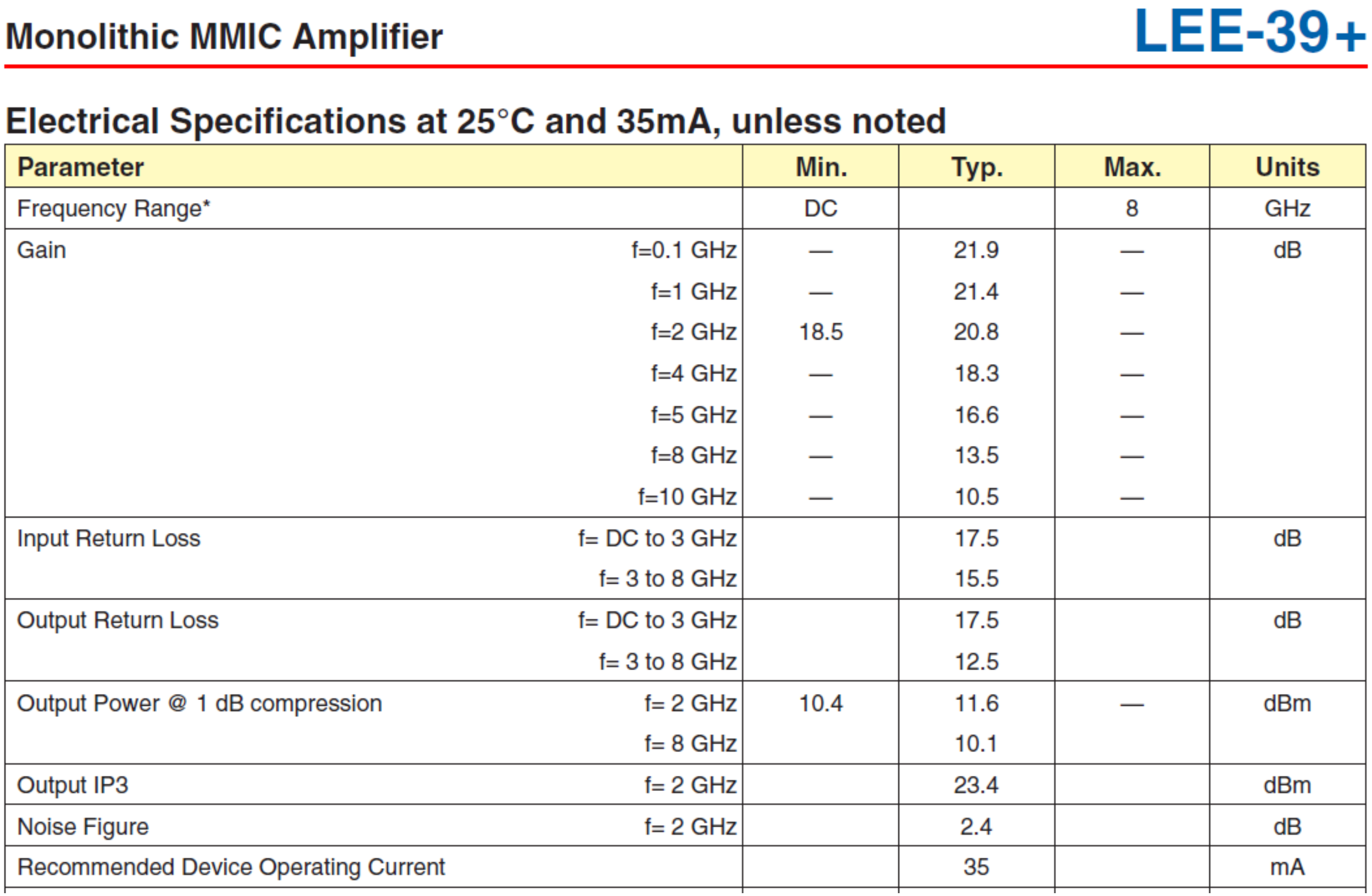


Source: Mini Circuits LEE-39 data sheet



Useful for many types of photodetectors. Example with photodiode shown, but can also be useful as an inline amplifier (long cables) or for small SiPMs

Circuit Architectures: MMIC amplifier



Monolithic MMIC Amplifier

LEE-39+

Electrical Specifications at 25°C and 35mA, unless noted

Parameter		Min.	Typ.	Max.	Units
Frequency Range*		DC		8	GHz
Gain	f=0.1 GHz	—	21.9	—	dB
	f=1 GHz	—	21.4	—	
	f=2 GHz	18.5	20.8	—	
	f=4 GHz	—	18.3	—	
	f=5 GHz	—	16.6	—	
	f=8 GHz	—	13.5	—	
	f=10 GHz	—	10.5	—	
Input Return Loss	f= DC to 3 GHz		17.5		dB
	f= 3 to 8 GHz		15.5		
Output Return Loss	f= DC to 3 GHz		17.5		dB
	f= 3 to 8 GHz		12.5		
Output Power @ 1 dB compression	f= 2 GHz	10.4	11.6	—	dBm
	f= 8 GHz		10.1		
Output IP3	f= 2 GHz		23.4		dBm
Noise Figure	f= 2 GHz		2.4		dB
Recommended Device Operating Current			35		mA

Reasonable supply current, low noise figure, and wideband response down to DC for 50Ω systems

Circuit Architectures: RF Transformer

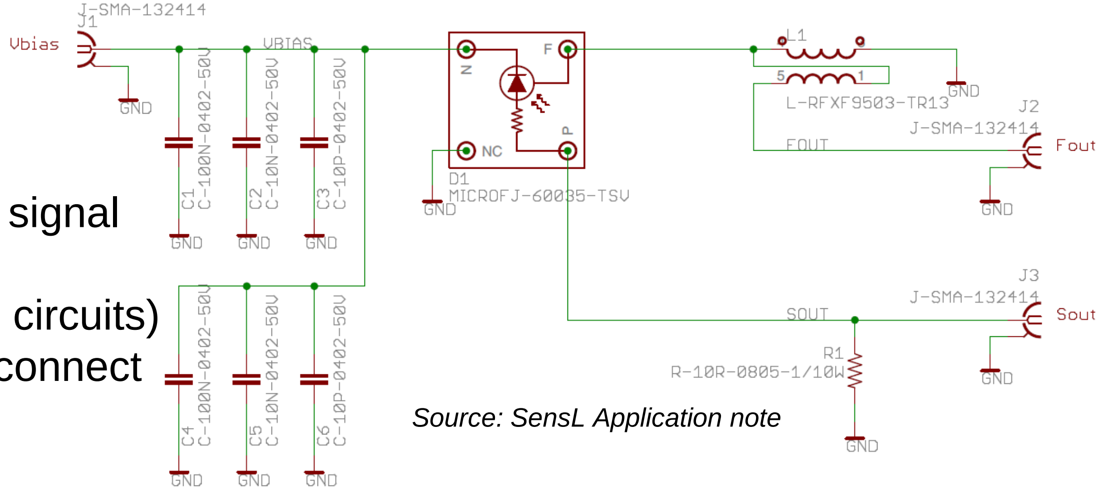
Transforms the 50 ohm system impedance to 50/4 or 12.5Ω

Advantages

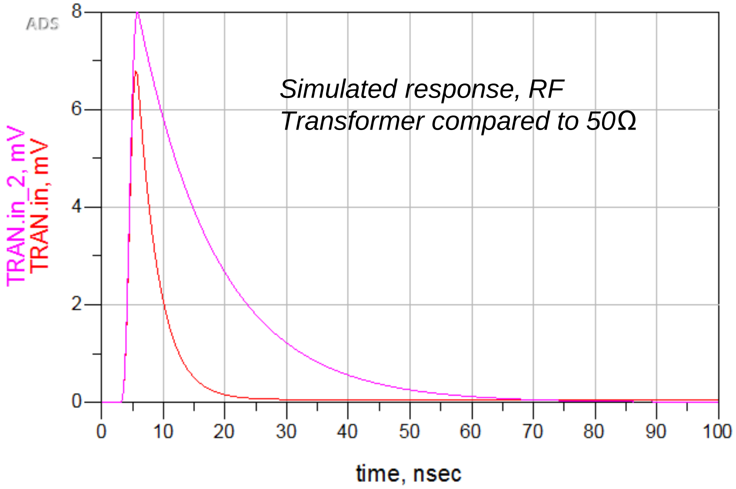
- Moderate Bandwidth
- Low input impedance improves signal time response
- Low noise/low power (no active circuits)
- Direct interface to 50 ohm interconnect

Disadvantages

- Fixed gain
- Sensitive to hysteresis/saturation
- **Sensitive to magnetic fields**
- AC coupled (separate monitor needed for DC current readout)



Source: SensL Application note



Simulated response, RF Transformer compared to 50Ω

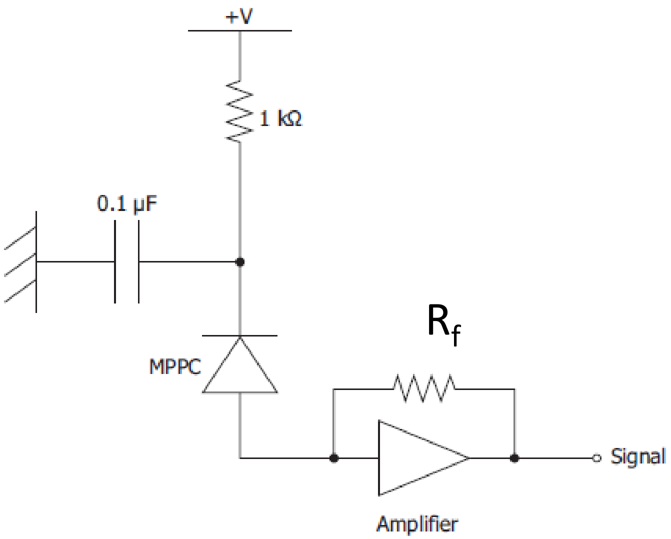
Circuit Architectures: Transimpedance Amplifier

Transforms the input current to an output voltage $V_{out}=i_{in}*R_f$

Advantages
- Moderate Bandwidth
- Low input impedance improves signal time response
- Adjustable transimpedance
- Response to DC

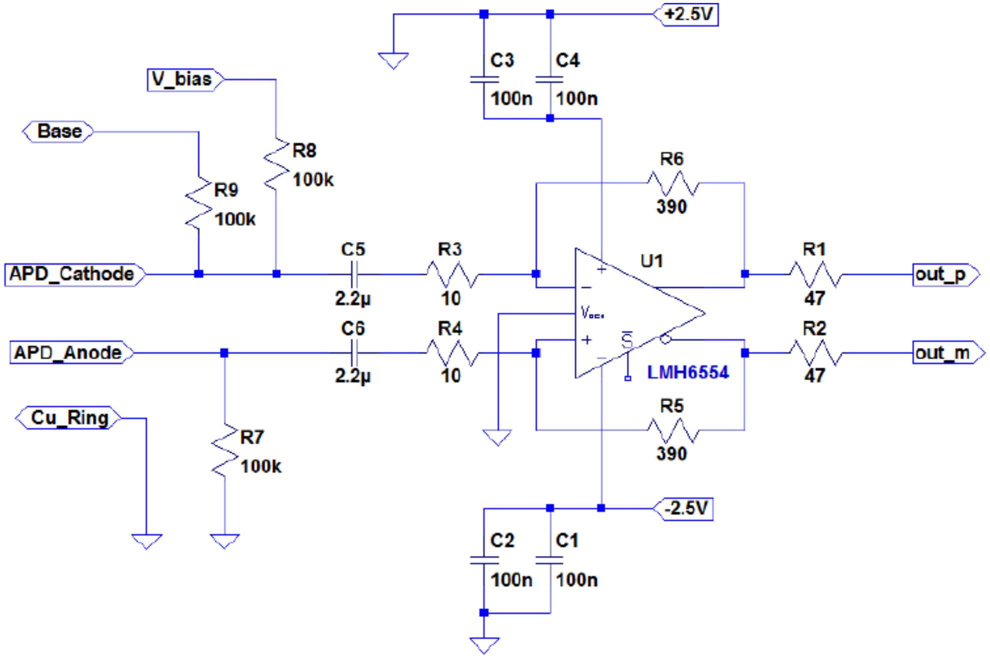
Disadvantages
- Device capacitance combined with R_f is a low pass filter which may cause resonance at some frequency
- Commonly used operational amplifier parts have poor noise figure
- Input/output impedances may be frequency dependant

Basic connection diagram

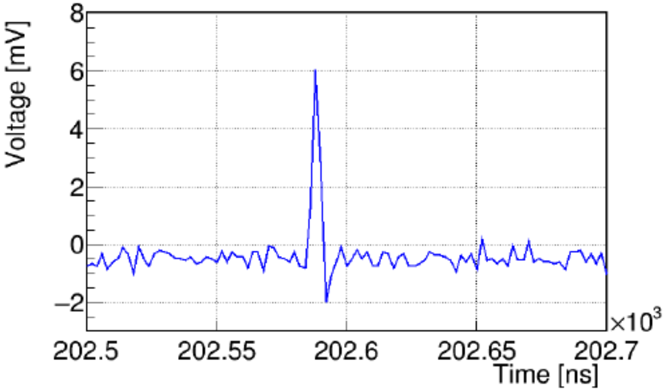


Circuit Architectures: Differential Transimpedance Amplifier Example

- Based on LMH6554
- R_f is 390Ω in this example
- In practice, R3 and R4 were set to 0
- Used with HPD for LIDAR, has not been tested with SiPM
- Power dissipation is 260 mW

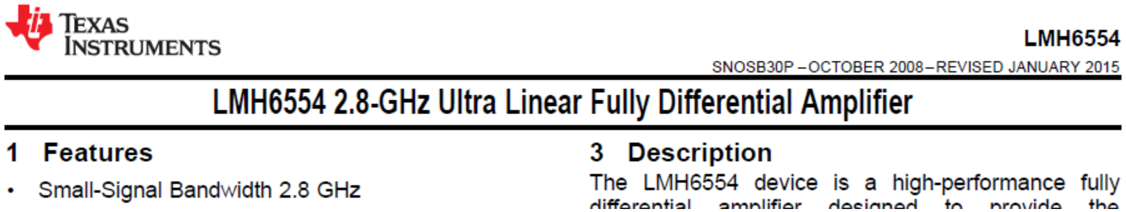


Single Photon:



Circuit Architectures: Differential Transimpedance Amplifier Example

- The data sheet says 2.8 GHz, but that depends on a number of factors (signal amplitude, feedback resistor, etc)
- The noise figure not that great
- The output impedance becomes significant at few hundred MHz



TEXAS INSTRUMENTS

LMH6554

SNOSB30P – OCTOBER 2008 – REVISED JANUARY 2015

LMH6554 2.8-GHz Ultra Linear Fully Differential Amplifier

1 Features

- Small-Signal Bandwidth 2.8 GHz

3 Description

The LMH6554 device is a high-performance fully differential amplifier designed to provide the

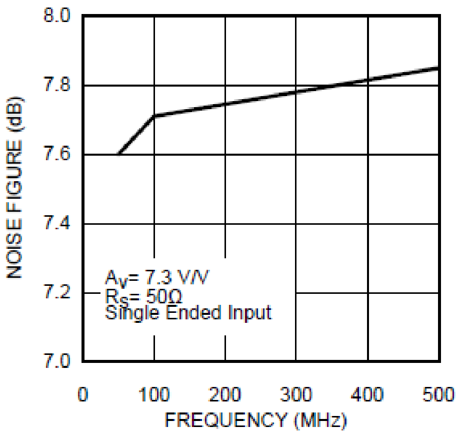


Figure 15. Noise Figure vs Frequency

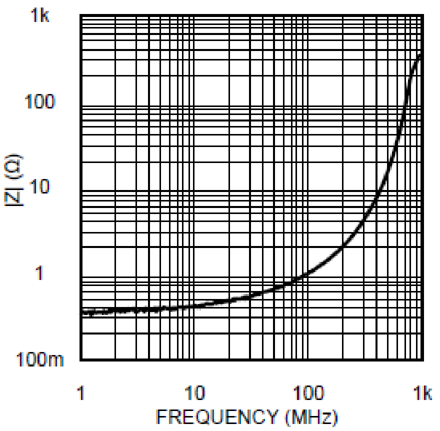
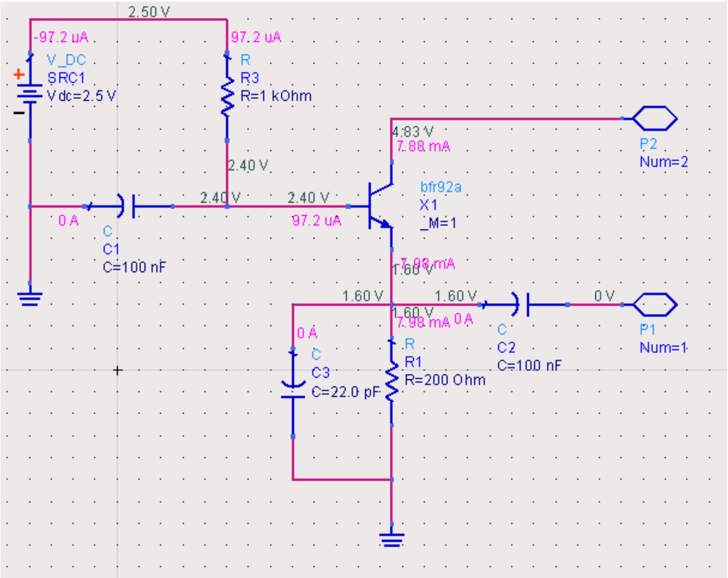


Figure 23. Closed-Loop Output Impedance

This approach looks better on paper, but may be suitable for some applications

Circuit Architectures: Common Base Transistor

Current output signal is roughly the same as the input current signal, but while the input impedance is low (<10Ω) the ouptut impedance is high like a current source



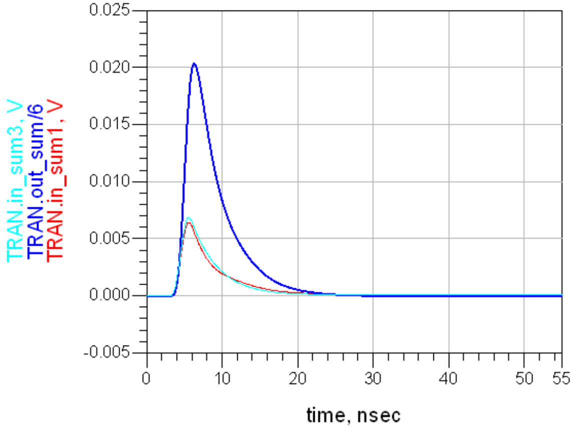
Advantages

- Good Bandwidth using common BFR92 RF NPN transistor
- Low input impedance improves signal time response
- Can be summed simply at the output for <10 devices
- Relatively low power (7ma@5v per circuit)

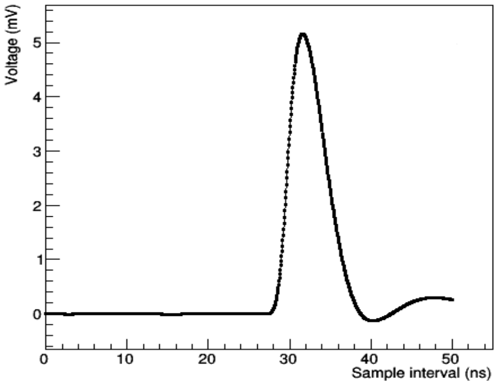
Disadvantages

- AC coupled
- Low impedance requires careful PCB layout

Time Domain Response (Simulation)



Time Domain Response (Measured Average)



Circuit Architectures: Summation Example 1

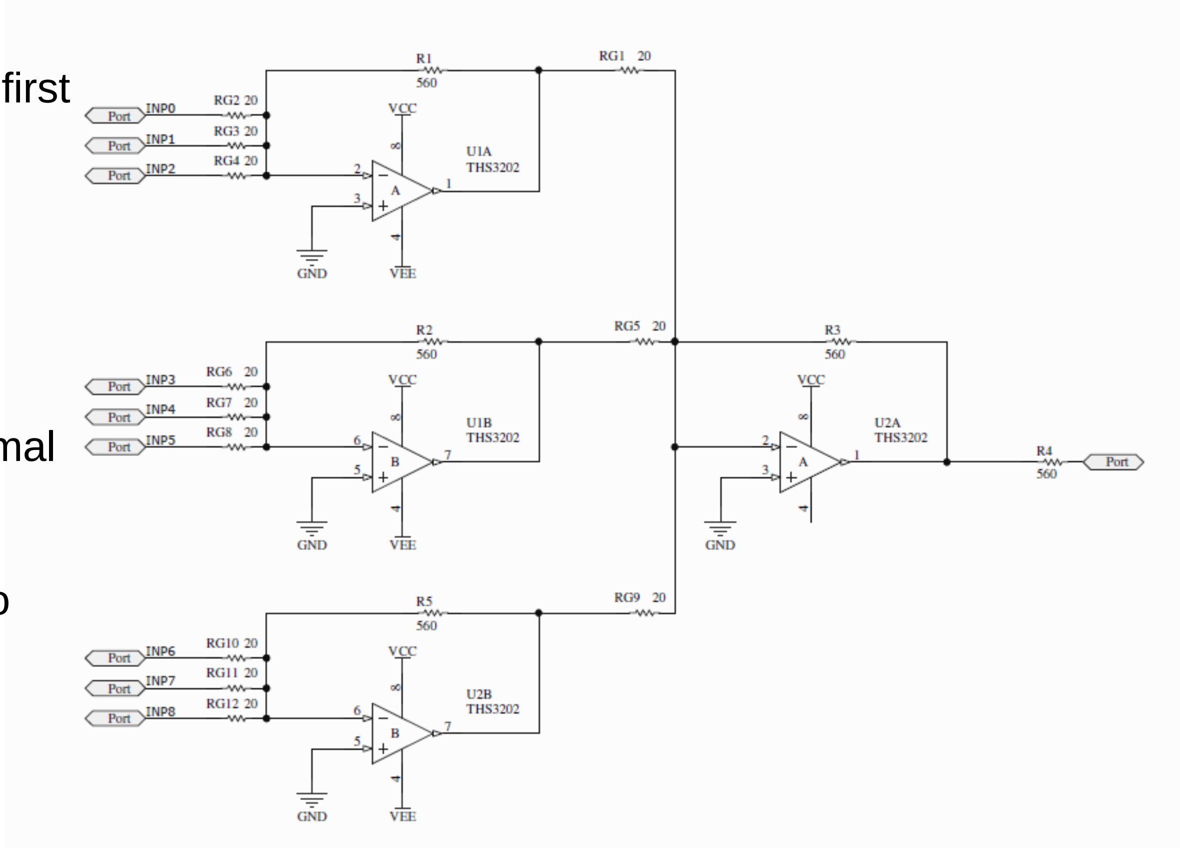
Output voltage is the sum of input voltages, what one would normally try first

Advantages

- Good power supply immunity
- Adjustable gain

Disadvantages

- Poor noise performance due to poor opamp performance, thermal resistance noise, and when the gain is not all in the first stage
- High power consumption due to additional stages
- Dynamic range may be limited



Circuit Architectures: Summation Example 3

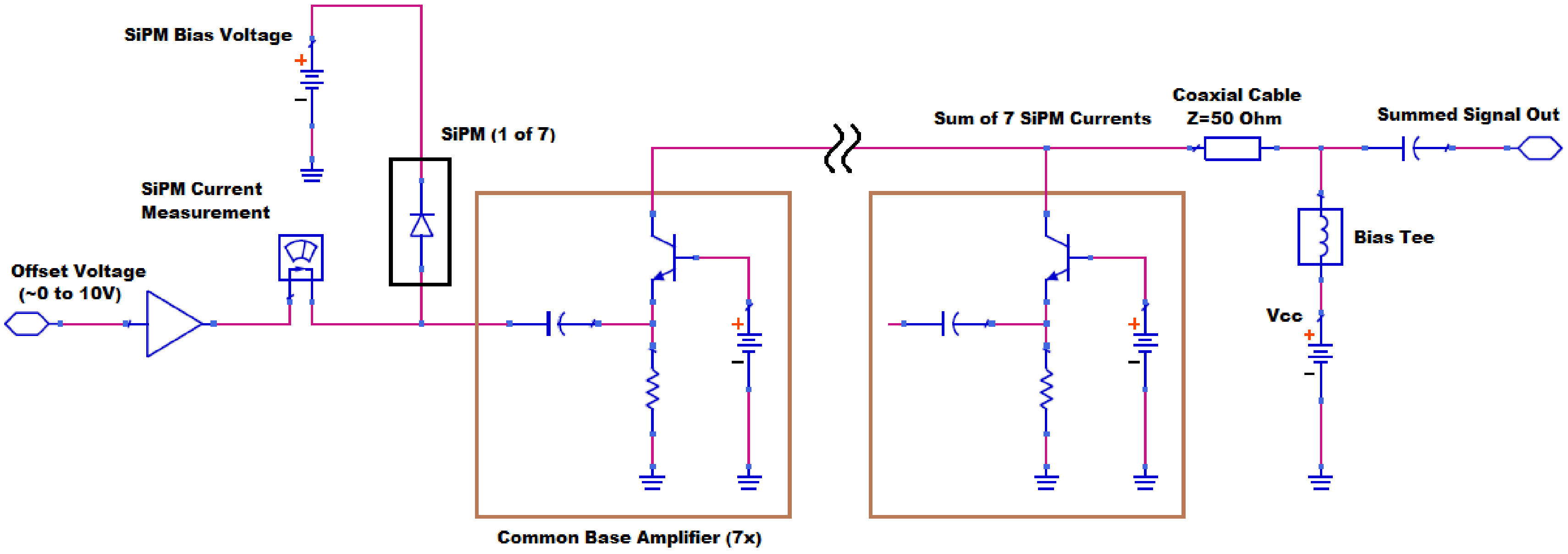
Output current is summed by connecting multiple common base circuits in parallel

Advantages

- Low input impedance suitable for the larger SiPM devices
- Good noise performance
- Unlike passive schemes, suitable for higer dark and signal rates

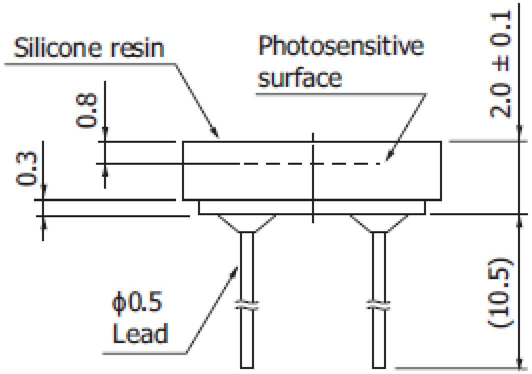
Disadvantages

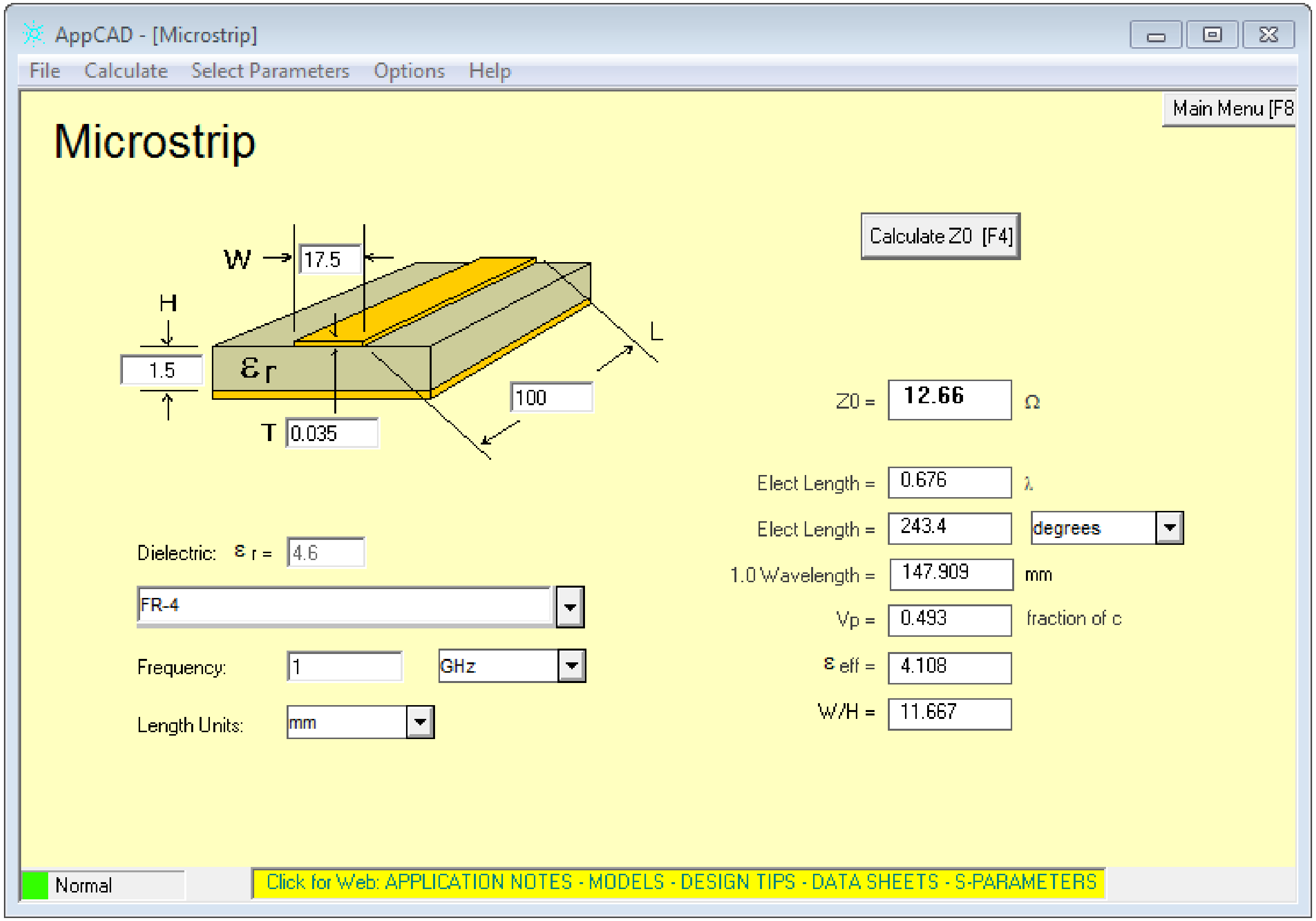
- Fixed voltage gain proportional to ratio of input to output impedance
- Unwieldy for large surface areas -> switch to ASIC design



PCB Interconnect

- Traces matched to 12.5Ω (necessary for low input impedance circuits) are unreasonably large on 1.5mm FR-4
- Alternative is to keep low impedance connection as short as possible
- Avoid sockets, connectors, vias, etc.
- Use surface mount packages if available
- Example: pin dia. 0.5mm and length 5mm has L~3 nH





W: 17.5

H: 1.5

T: 0.035

L: 100

Dielectric: εr = 4.6

FR-4

Frequency: 1 GHz

Length Units: mm

Z0 = 12.66 Ω

Elect Length = 0.676 λ

Elect Length = 243.4 degrees

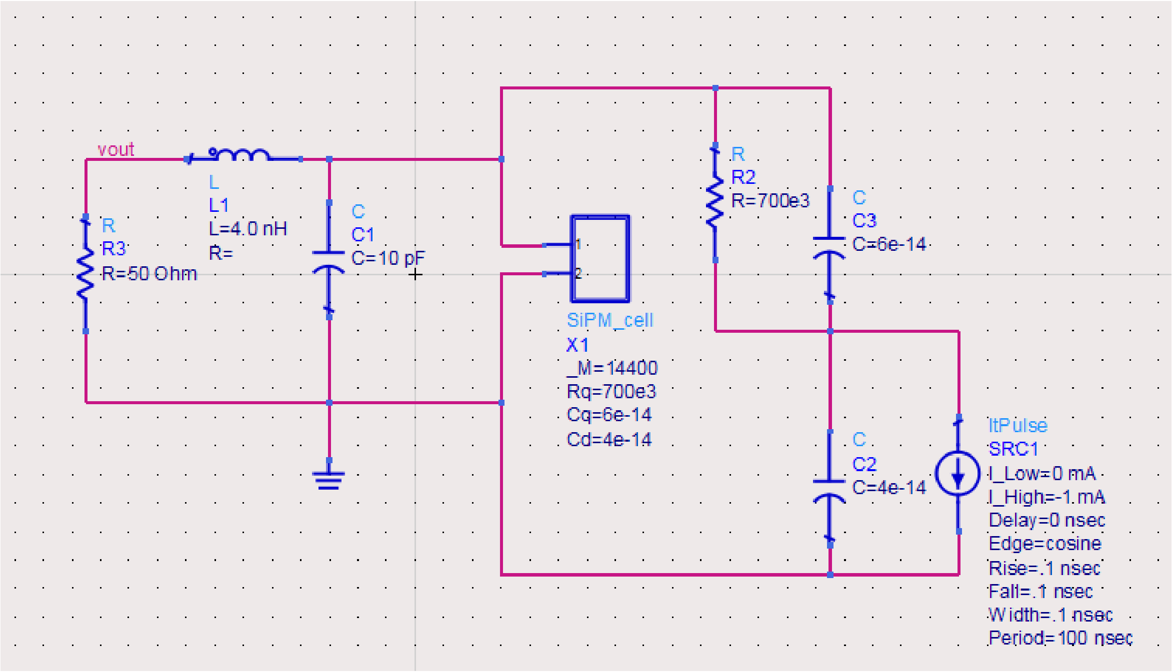
1.0 Wavelength = 147.909 mm

Vp = 0.493 fraction of c

ε eff = 4.108

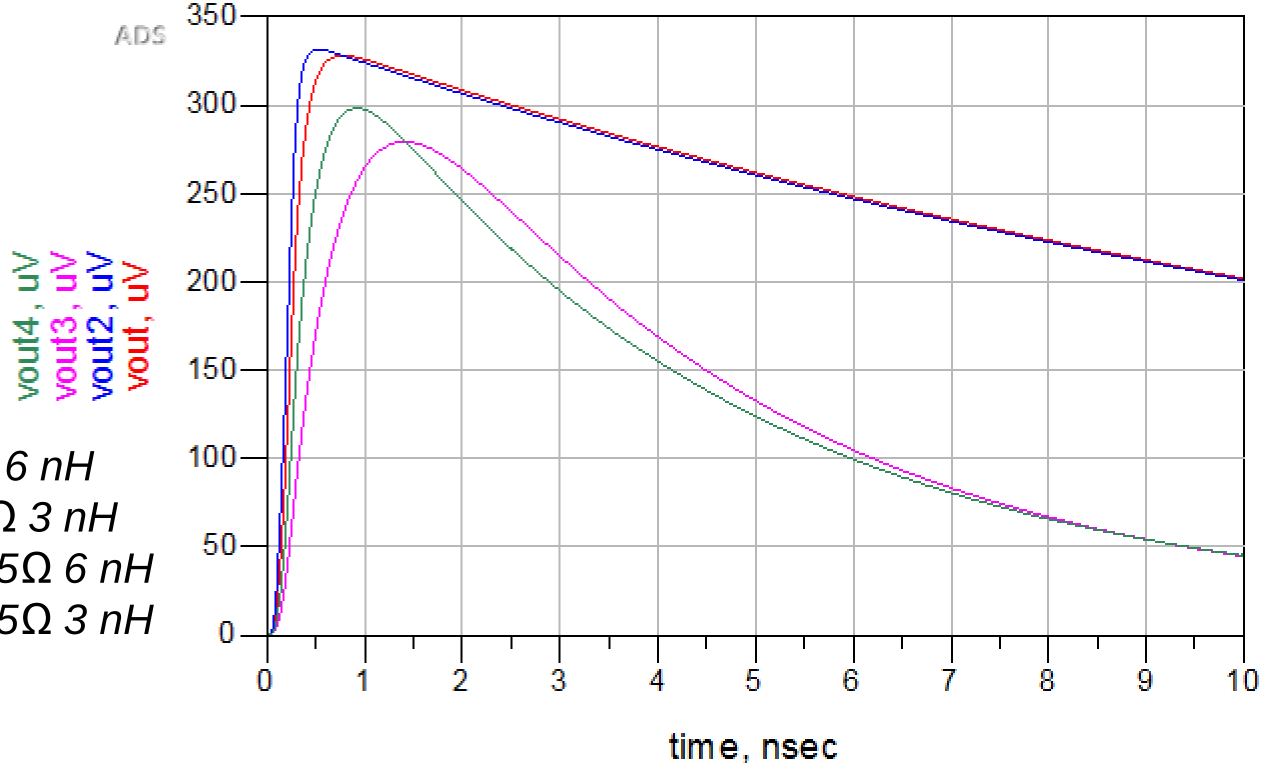
W/H = 11.667

Simple SiPM simulation model for investigating effects of parasitics on signal waveforms



- Each SiPM cell modeled as a quench resistor with parallel capacitance and diode capacitance
- 10 pF included for on-chip interconnect
- Series inductance of several nH
- One cell has a 100ps input current pulse
- 14400 additional passive cells (corresponding to 6x6 SiPM)
- Voltage sampled across load resistance

Simulation Results for four different combinations of input resistance and series inductance

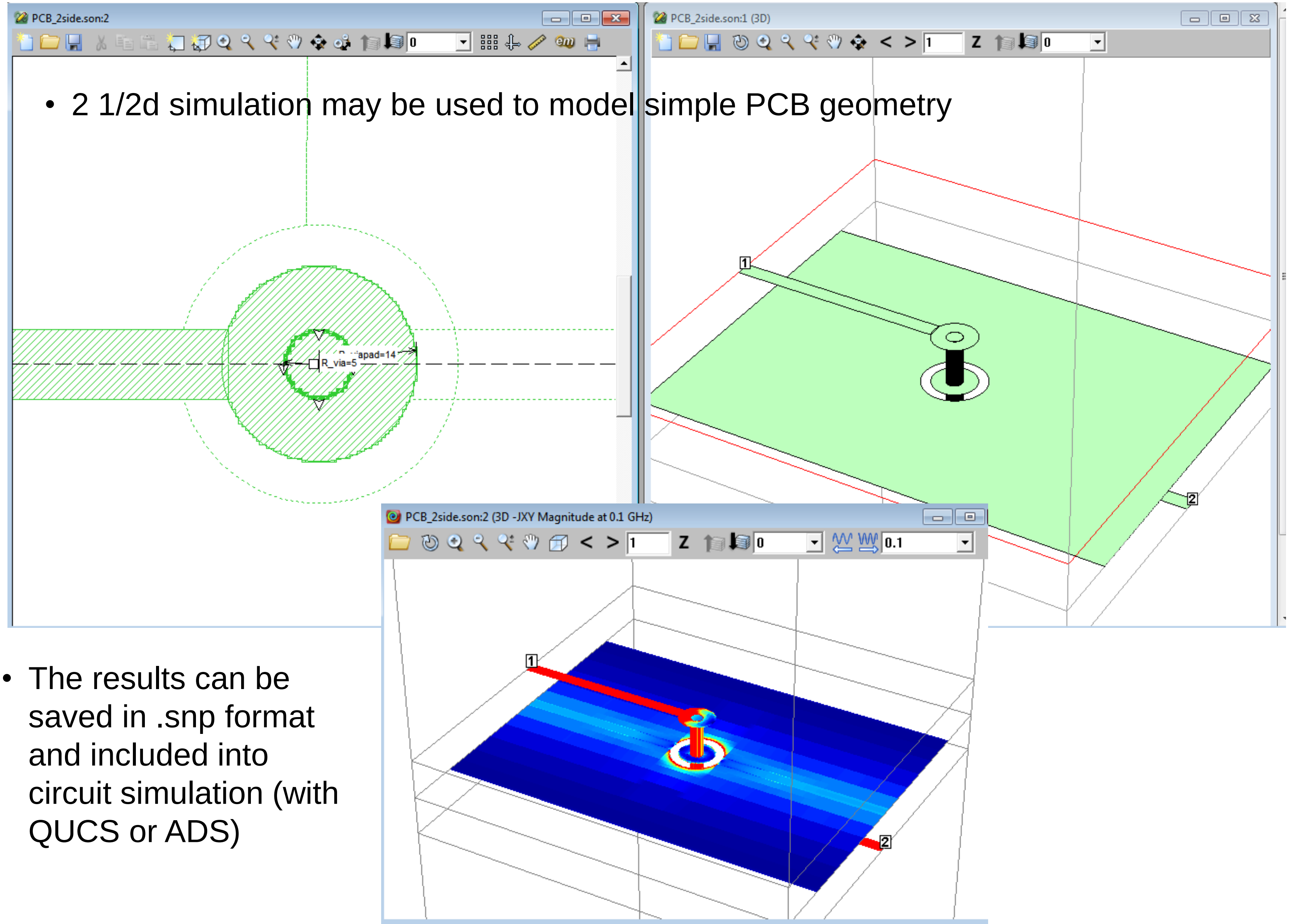


Vout 50Ω 6 nH
Vout2 50Ω 3 nH
Vout3 12.5Ω 6 nH
Vout4 12.5Ω 3 nH

The output signal is sensitive to relatively small additional series inductance at low input impedance – in this case 3 nH equivalent to a package pin

PCB Interconnect

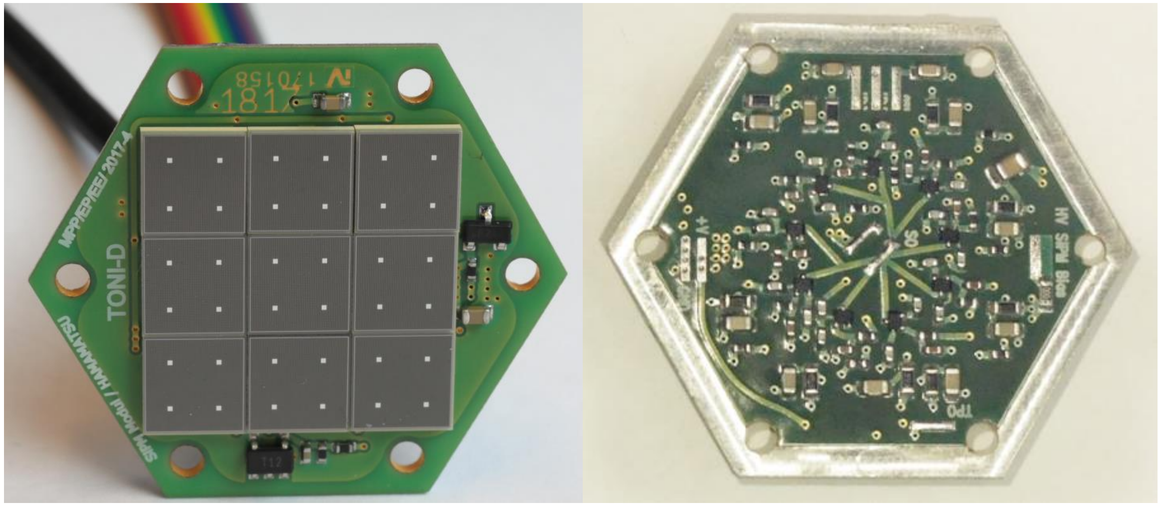
- 2 1/2d simulation may be used to model simple PCB geometry

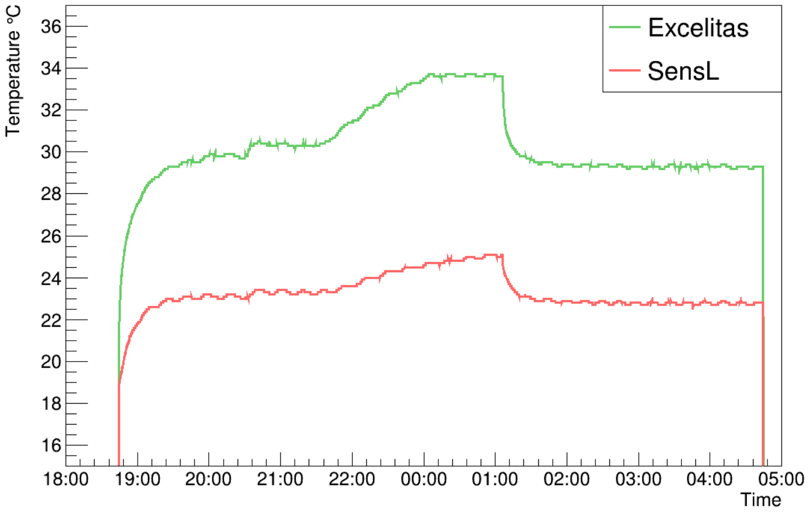


- The results can be saved in .snp format and included into circuit simulation (with QUCS or ADS)

PCB Interconnect Example

- Example of high density discrete design
- Short connections with output stage directly under the SiPMs
- Operation at high light levels also meant significant power dissipation
- To conduct heat to the supporting structure, aluminum core PCBs were used
- Graph at lower right compares temperature vs time during operation:
    - Green is FR-4 PCB, red is aluminum core PCB





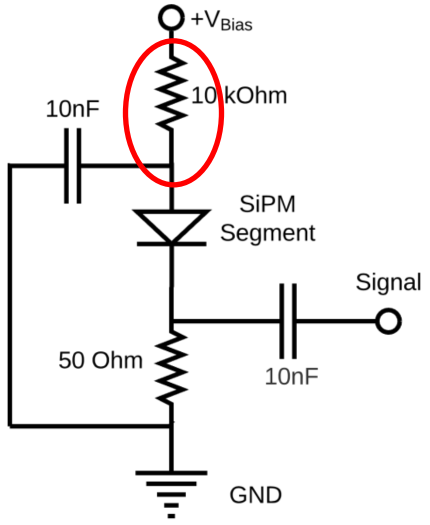
SiPM bias supply and current limiting

Lab settings can use low noise analog power supplies
Experimental equipment may require local power circuitry

- High count rates may require mA of supply current
- Switch mode DC/DC converters may generate conductor bound or radiated „spikes“- these may be hard to distinguish from signal events
- Some form of current limit is desirable to preclude thermal detector damage
- A combination of a fixed low noise DC/DC converter and a linear regulator is one option proven to work
- If possible, supply circuits should be placed some distance away from the detector

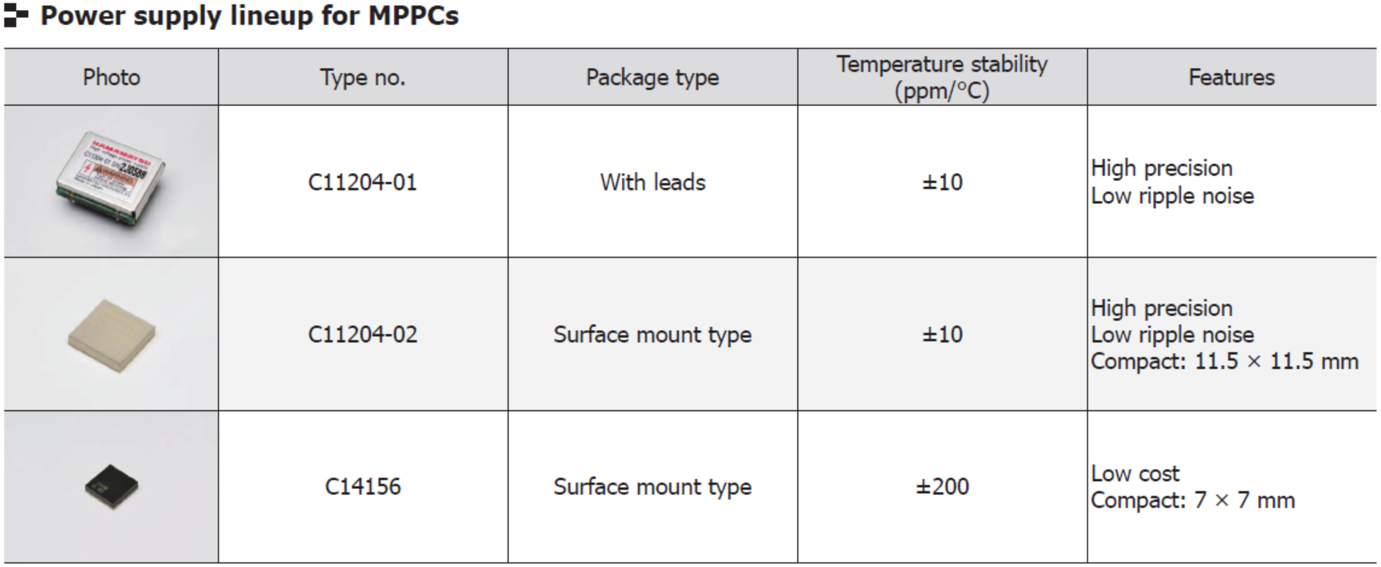
Use of an inductance or low resistance in the supply filter to avoid bias dependance on current consumption

The voltage drop across the resistor often used in simple bias voltage filter circuits can make your bias voltage and thus SiPM gain dependent on light level



SiPM bias supply and current limiting

Commercial power modules are now available which may be appropriate for many applications

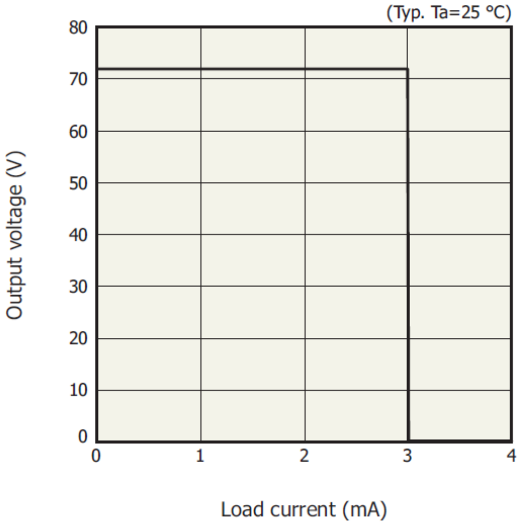


Power supply lineup for MPPCs

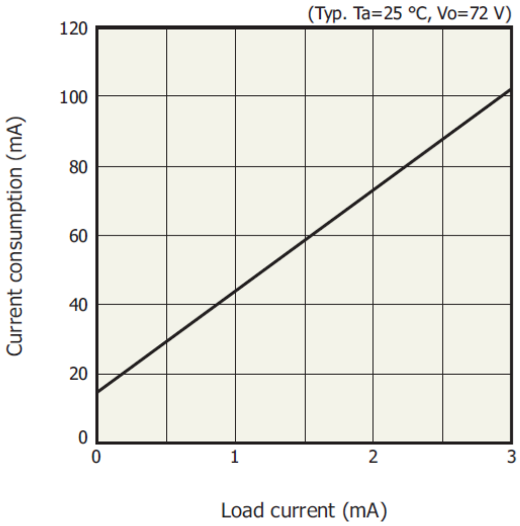
Photo	Type no.	Package type	Temperature stability (ppm/°C)	Features
	C11204-01	With leads	±10	High precision Low ripple noise
	C11204-02	Surface mount type	±10	High precision Low ripple noise Compact: 11.5 × 11.5 mm
	C14156	Surface mount type	±200	Low cost Compact: 7 × 7 mm

Some characteristics may preclude their use in your application, for example:

- Low efficiency
- Low output current
- Serial control interface



Output voltage vs. load current



Current consumption vs. load current

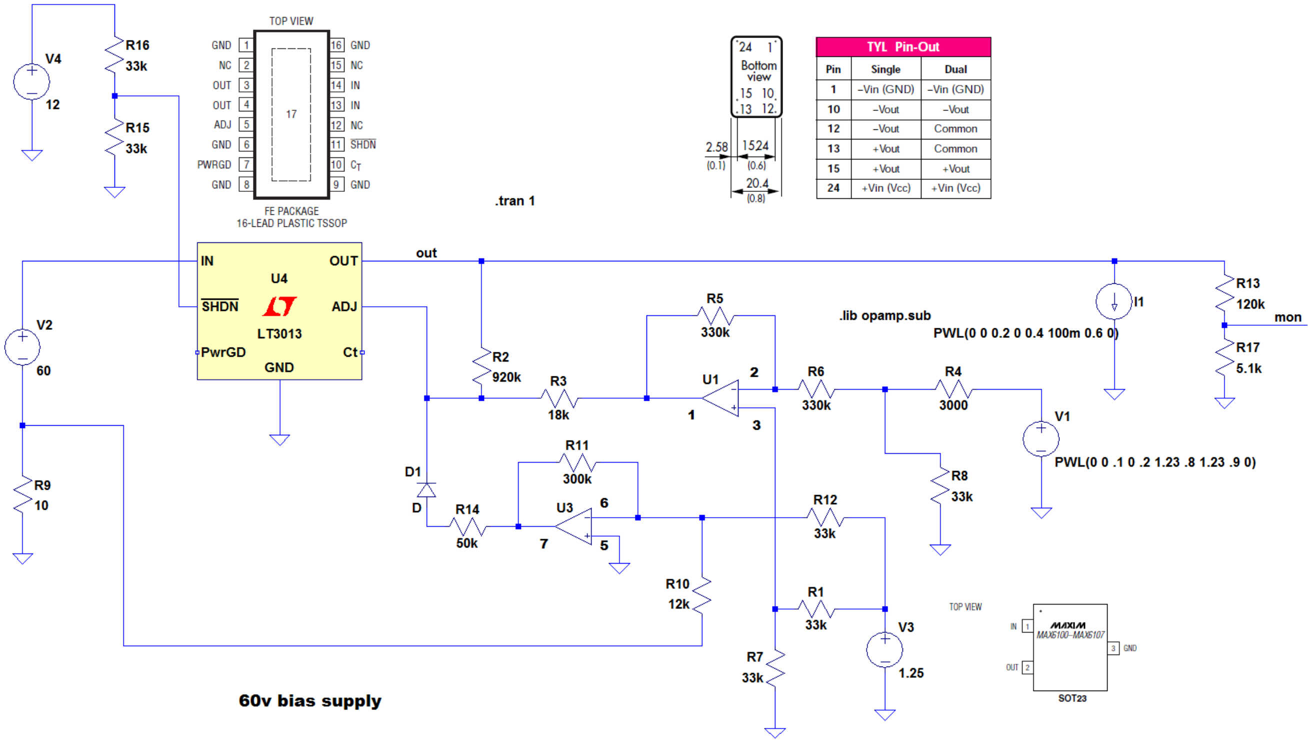
Sample SiPM bias supply with analog ouptut voltage control and current limiting

2x Traco TYL 05-15W05 low noise DCDC converters provide 60V supply from 5V

Linear regulator (LT3013) provides filtering and adjustable output controlled by 0-1.25V analog voltage

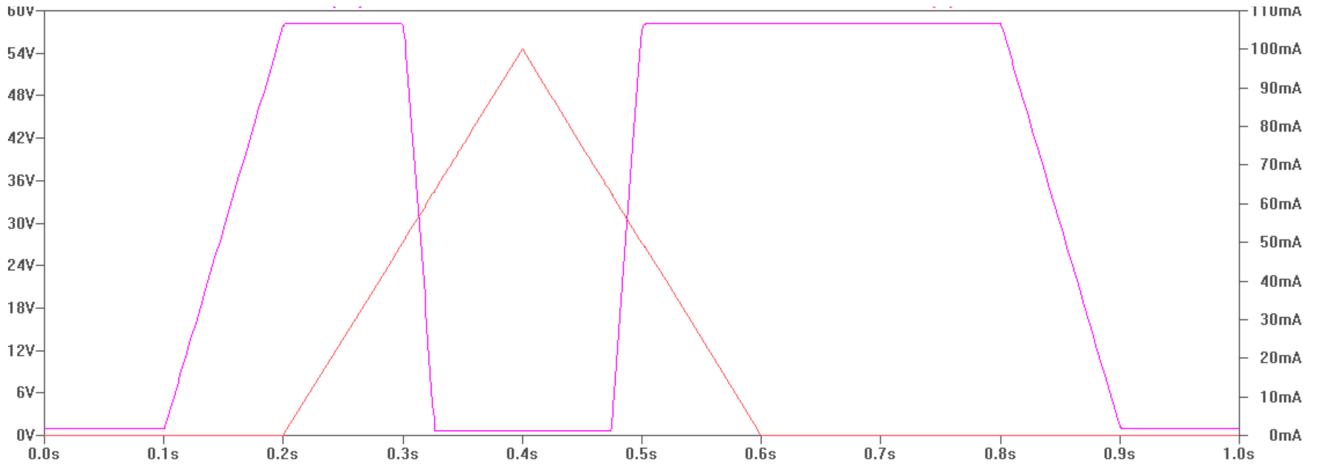
50 mA max. supply current for high light intensity environment

Simulation shows outut response to control input (magenta), overcurrent shutdown (current shown in red)

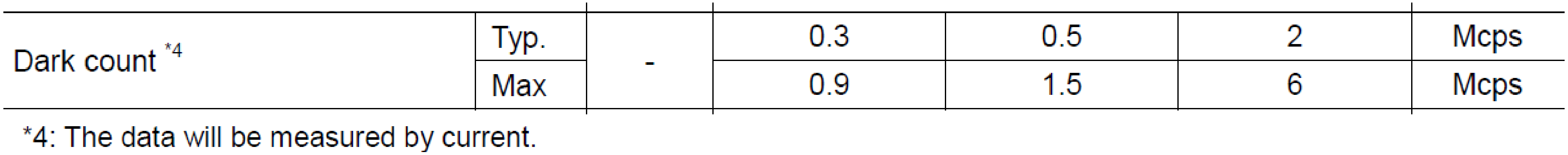


TYL Pin-Out		
Pin	**Single**	**Dual**
1	–Vin (GND)	–Vin (GND)
10	–Vout	–Vout
12	–Vout	Common
13	+Vout	Common
15	+Vout	+Vout
24	+Vin (Vcc)	+Vin (Vcc)

60v bias supply



A last comment on noise:



Dark count [4]	Typ.	-	0.3	0.5	2	Mcps
	Max		0.9	1.5	6	Mcps

*4: The data will be measured by current.

- Although dark current is specified for APDs, most SiPM data sheets do not list this figure
- In general, dark current is measured as a current converted to a dark count rate
- In many cases, calibration may be done using dark counts, which means they become signal. Additional dark current may become a significant contribution in this case

Comparison of signal to noise performance between different devices when calibrated using dark counts is not immediately obvious, especially for large detection areas

Some useful (free) tools for design:

Software name	Use	Link
LTspice	SPICE circuit simulator	https://www.analog.com/en/design-center/design-tools-and-calculators/ltspice-simulator.html
QUCS	ADS-like circuit simulator	https://sourceforge.net/projects/qucs/
Sonnet Lite	2 ½ D EM simulator	http://www.sonnetsoftware.com/products/lite/download.html
Appcad	Useful RF design calculator	https://www.broadcom.com/appcad

You can get started investigating circuit design in your free time ☺