筑波大学数理物質科学研究科 物理学専攻

2016年6月24日
高エネルギー加速器研究機構
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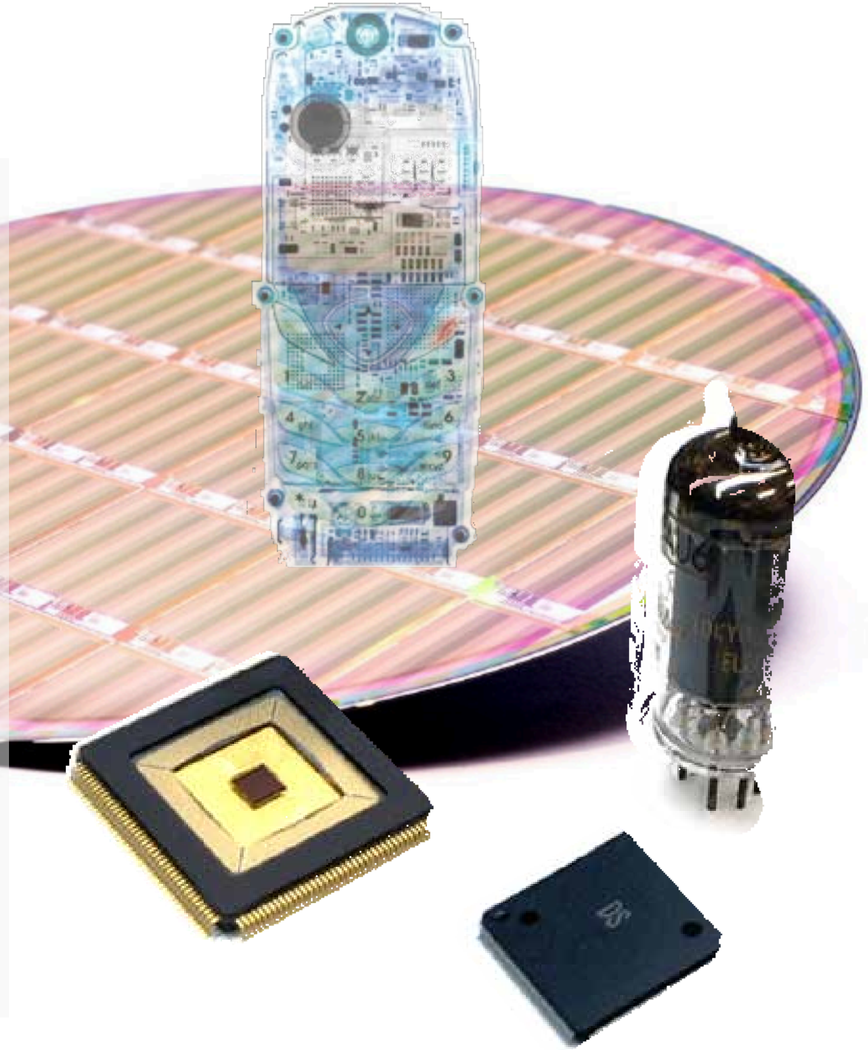
エレクトロニクス・データ処理
(放射線計測とLSI)
#2

- Lecture Schedule (金曜第3時限 12:15-13:30)
  June 17, 24
  July 1, 8, *15(No lecture)*, 22, 29
  Total 6 times
- Contents
  (http://research.kek.jp/people/araiy/16lecture/)
  - ❑ Radiation Measurement and LSI
  - ❑ Analog CMOS Circuit for Radiation Measurement
  - ❑ Digital LSI Circuit
  - ❑ Semiconductor Radiation Detector
- 単位認定(Credit)
  講義出席及びレポート
  (田中氏の分と合算)



Lecture Plan

1. Radiation measurement and LSI
   - 高エネルギー物理実験とLSI、
   - LSI技術の変遷
   - 半導体放射線検出器

2. Basic low and tools
   - オームの法則、
   - 信号伝送、
   - 信号規格 …

3. Semiconductor devices
   - 半導体の基礎、
   - 半導体プロセス、
   - MOSデバイス基礎、
   - …

4. Analog CMOS circuit
   - 1段増幅回路、差動増幅回路、
   - カレントミラー、
   - アナログ・シミュレーション、
   - オペアンプ回路、
   - 雑音, …

5. Digital LSI circuit
   - CMOS論理回路、メモリー、
   - 演算器、カウンター、同期回路,
   - 順序回路、ADC, TDC、…
   - 論理合成

6. Semiconductor radiation detector
   - 放射線の相互作用
   - 検出器の動作原理、
   - 実例、…

Ohm's law

Ohm's law states that the current through a conductor between two points is directly proportional to the potential difference across the two points. The law was named after the German physicist Georg Ohm, published in 1827. (Wikipedia)

$$V = I \cdot R$$

DC

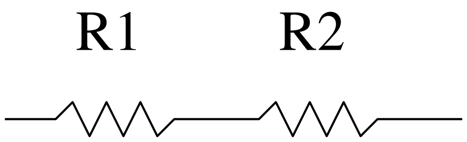
Resistance : R [Ω]
Conductance : G = 1/R [S*(iemens)*]

AC

Impedance : Z [Ω]
Admittance : Y=1/Z [S]

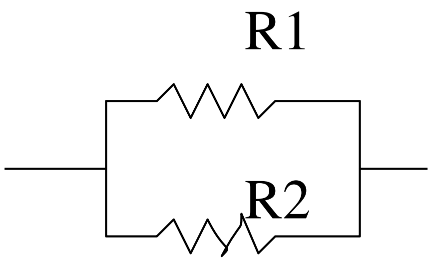
Z = R + iX
X : Reactance
Y = G + iB
B : Susceptance

Series Connection of Resister



$$R = R1 + R2$$

Parallel Connection of Resistor



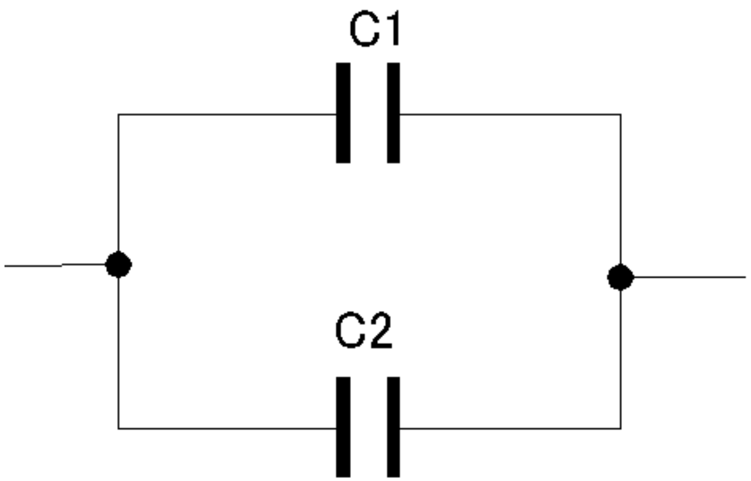
$$R = \frac{1}{\frac{1}{R1} + \frac{1}{R2}} = \frac{R1 \cdot R2}{R1 + R2}$$

$$\Rightarrow R1 // R2$$

Series connection of Capacitor

$$C = \frac{1}{\frac{1}{C1} + \frac{1}{C2}} = \frac{C1 \cdot C2}{C1 + C2}$$

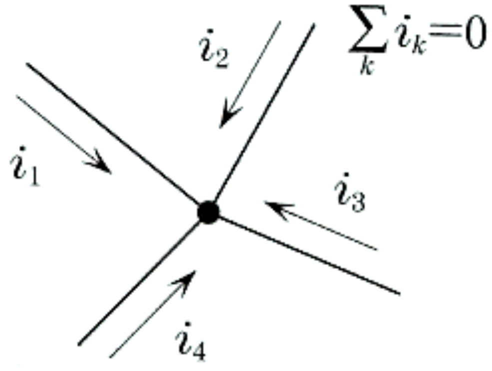
Parallel connection of Capacitor



$$C = C1 + C2$$

Kirchhoff's law

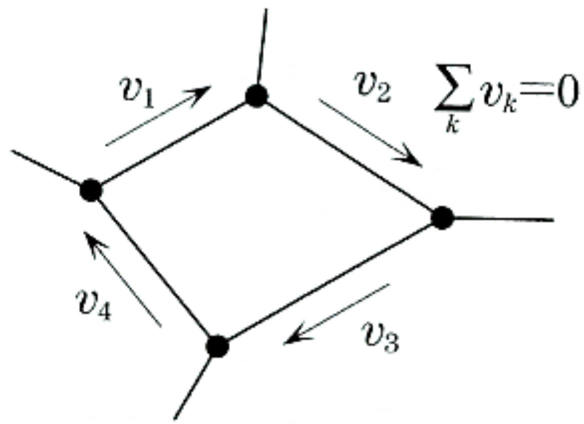
The sum of currents flowing into any node and the sum of the voltage around any closed network are zero. They were first described in 1845 by German physicist Gustav Kirchhoff. (Wikipedia)



Current law（Kirchhoff's first law）

電気回路の任意の節点において、流れ込む向きを正（又は負）と統一すると、各線の電流をi_kとしたとき、その総和は0となる。

$$\sum_{k=1}^{N} i_k = 0$$



Voltage law（Kirchhoff's first law）

電気回路に任意の閉路をとり電圧の向きを一方向に取ったとき、各区間の電圧をv_kとすると、電圧の総和は0となる。

$$\sum_{k=1}^{N} v_k = 0$$

Thévenin's theorem (テブナンの定理)

Any linear electrical network with voltage and current sources and resistances can be replaced by an equivalent voltage source V_{Th} in series connection with an equivalent resistance R_{Th}. The theorem was derived in 1883 by French engineer Léon Charles Thévenin.
日本では等価電圧源表示、また独自に発表した鳳秀太郎（東大工学部教授で与謝野晶子の実兄）の名を取って、鳳-テブナンの定理ともいう。
(Wikipedia)

Thévenin equivalent circuit:

a voltage source with voltage V_{Th} in series with a resistance R_{Th}.

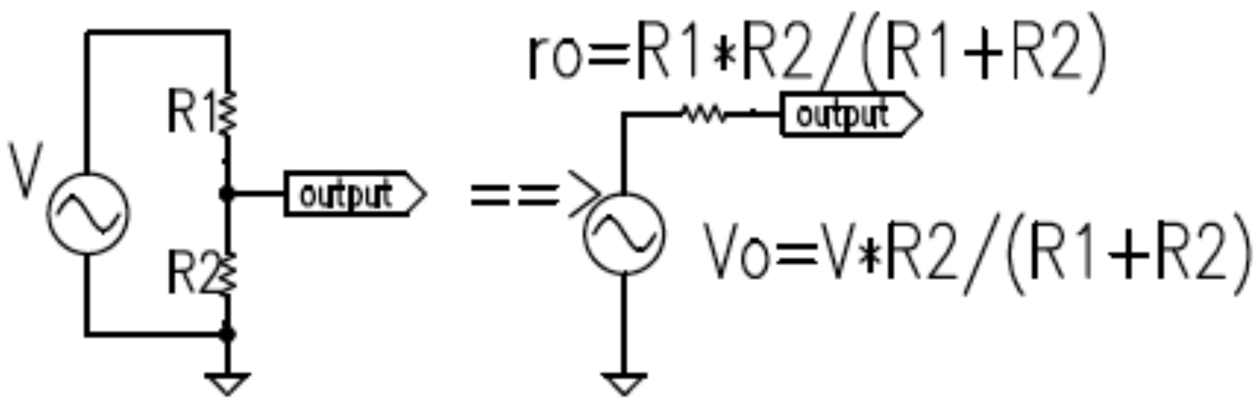
Norton equivalent circuit:

a current source I_{NO} in parallel connection with an resistance R_{NO}.

Thévenin equivalent circuit

1）Calculate the output voltage, Vo, when in open circuit condition.

2）Replace the independent voltage sources with short circuits, and independent current sources with open circuits. Then calculate the resistance of the output node r_o.

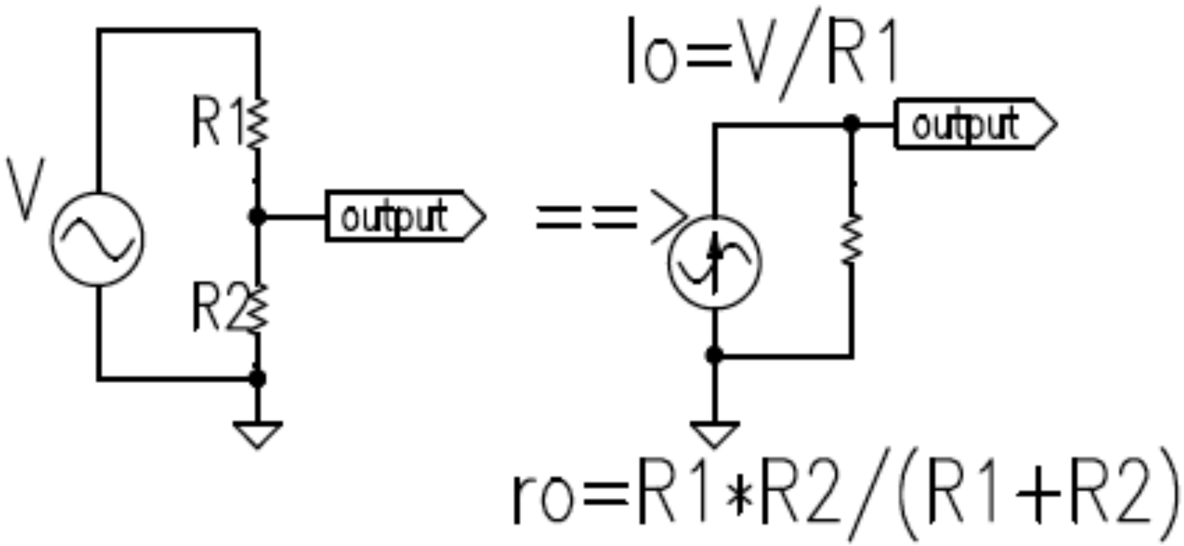


$$V_0 = V \times \frac{R_2}{R_1 + R_2}$$

$$r_0 = \frac{R_1 R_2}{R_1 + R_2}$$

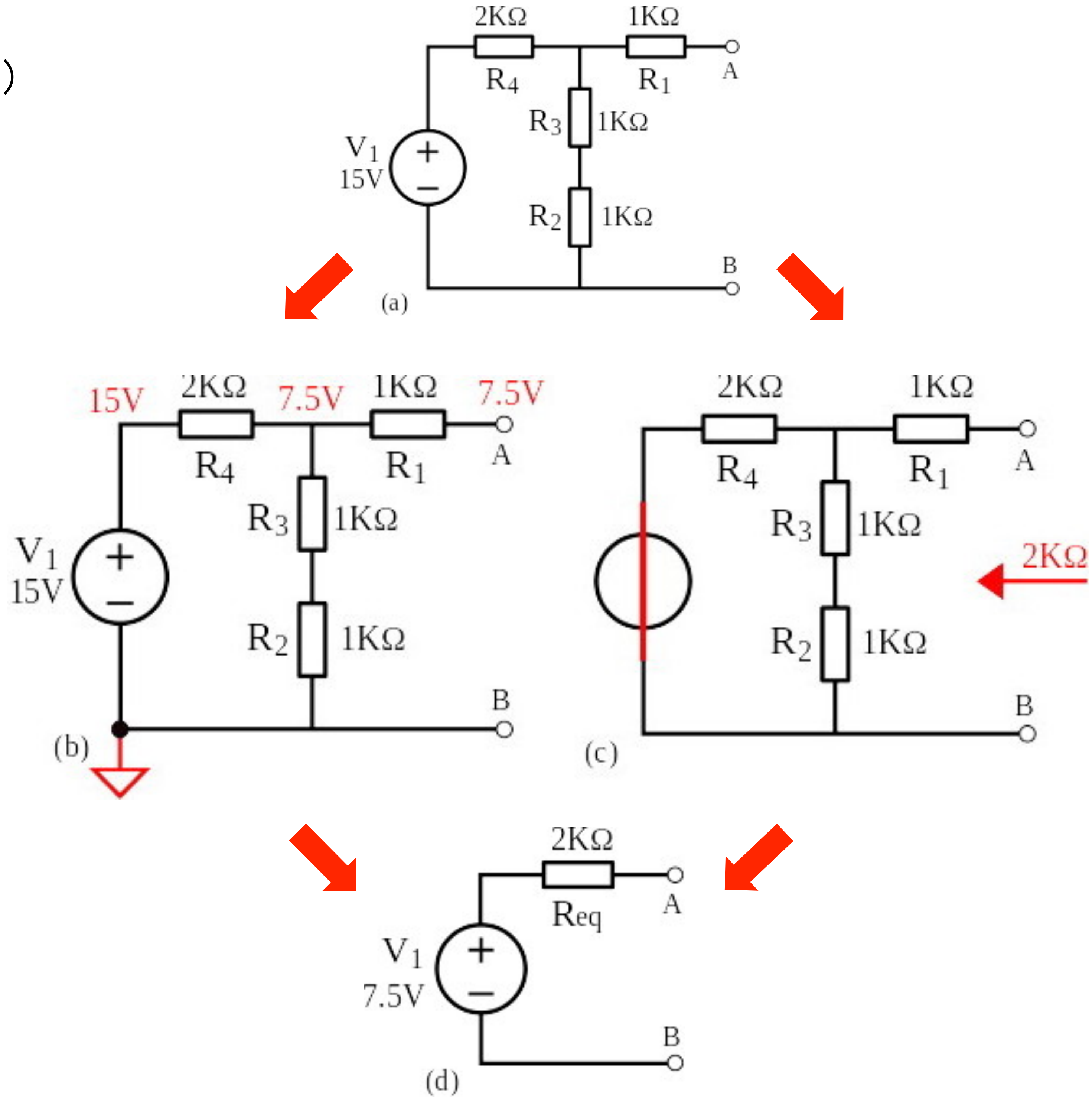
Norton equivalent circuit

3) from the V_0、Z_0、Put Current source of $I_0=V_0/Z_0$ and resistance Z_0 in parallel.



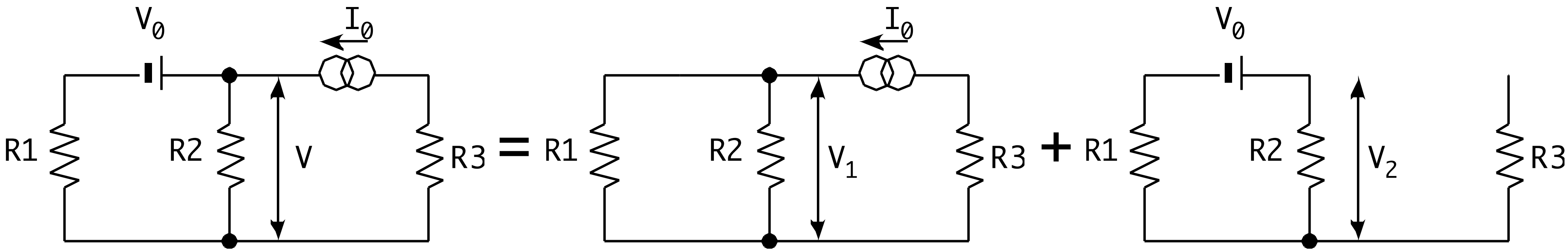
$$I_0 = \frac{V_0}{r_0} = \frac{VR_2}{R_1+R_2} \div \frac{R_1R_2}{R_1+R_2} = \frac{V}{R_1}$$

Ex.)


2KΩ
1KΩ
R4
R1
A
R3
1KΩ
V1
15V
R2
1KΩ
B
(a)
15V
2KΩ
7.5V
1KΩ
7.5V
R4
R1
A
R3
1KΩ
V1
15V
R2
1KΩ
B
(b)
2KΩ
1KΩ
R4
R1
A
R3
1KΩ
2KΩ
R2
1KΩ
B
(c)
2KΩ
Req
A
V1
7.5V
B
(d)

Principle of superposition

In electronics circuit which has several power supplies, current of any node and voltage between any two nodes are equal to the sum of the value when each supply exist independently by changing voltage sources to short and current sources to open.(Wikipedia)

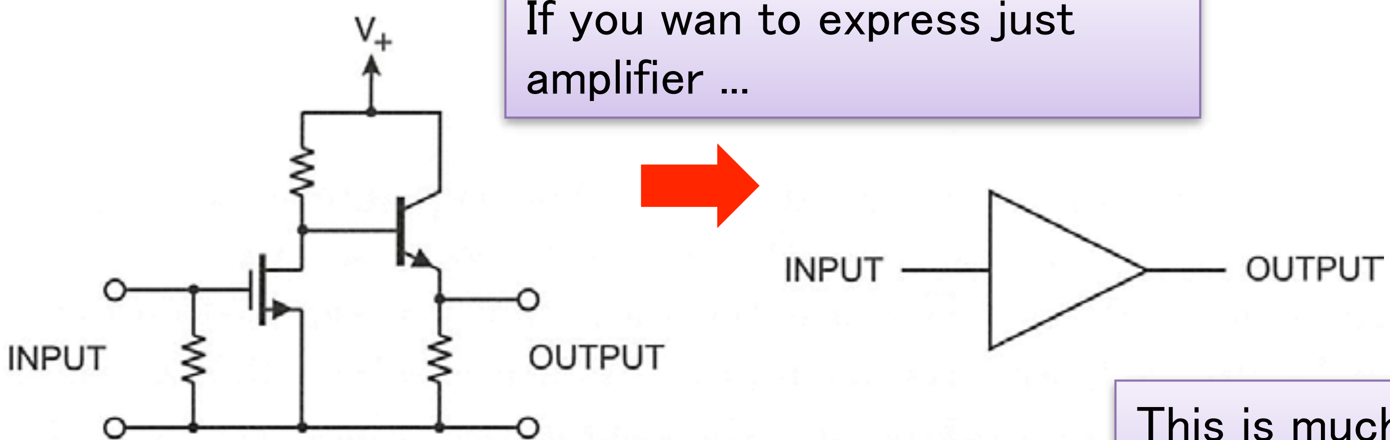


$$
\begin{aligned}
V &= V_1 + V_2 \\
&= \frac{R1 \cdot R2}{R1 + R2} I_0 + \frac{R2}{R1 + R2} V_0 \\
&= \frac{R2}{R1 + R2} (R1 \cdot I_0 + V_0)
\end{aligned}
$$

Equivalent Circuit

An equivalent circuit refers to a theoretical circuit that retains all of the electrical characteristics of a given circuit. That is a simplest form of a more complex circuit in order to aid analysis.

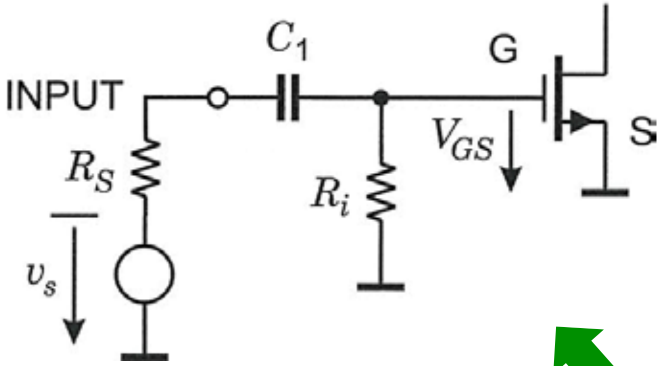
If you wan to express just amplifier …



This is much easier to understand

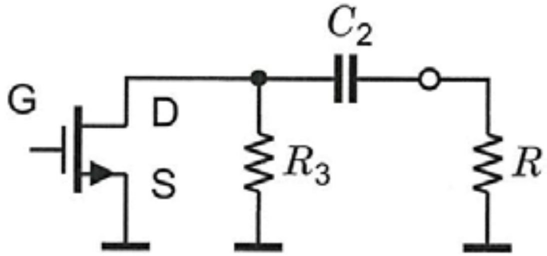
Therefore, you can write different equivalent circuit depend on your purpose.

Example of Equivalent Circuit

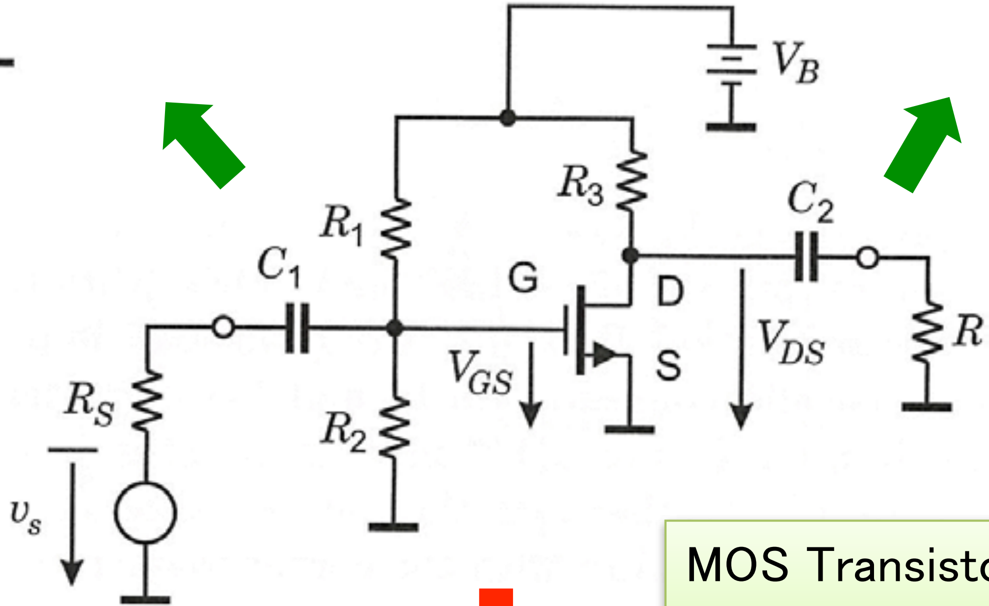


Bias R to Input R

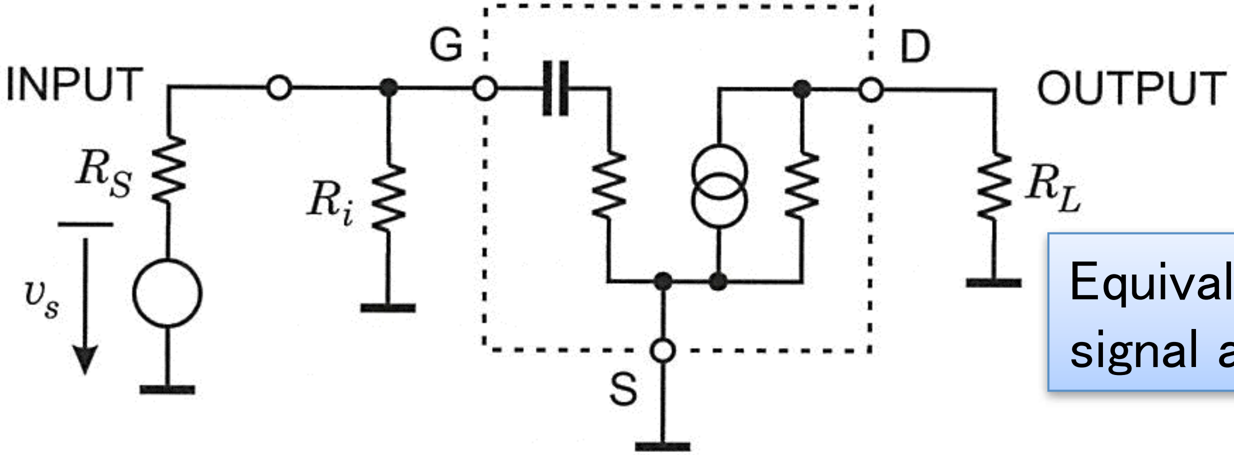
$$R_i = R_1 // R_2$$



Power Supply is equal to GND



MOS Transistor is Voltage to Current converter

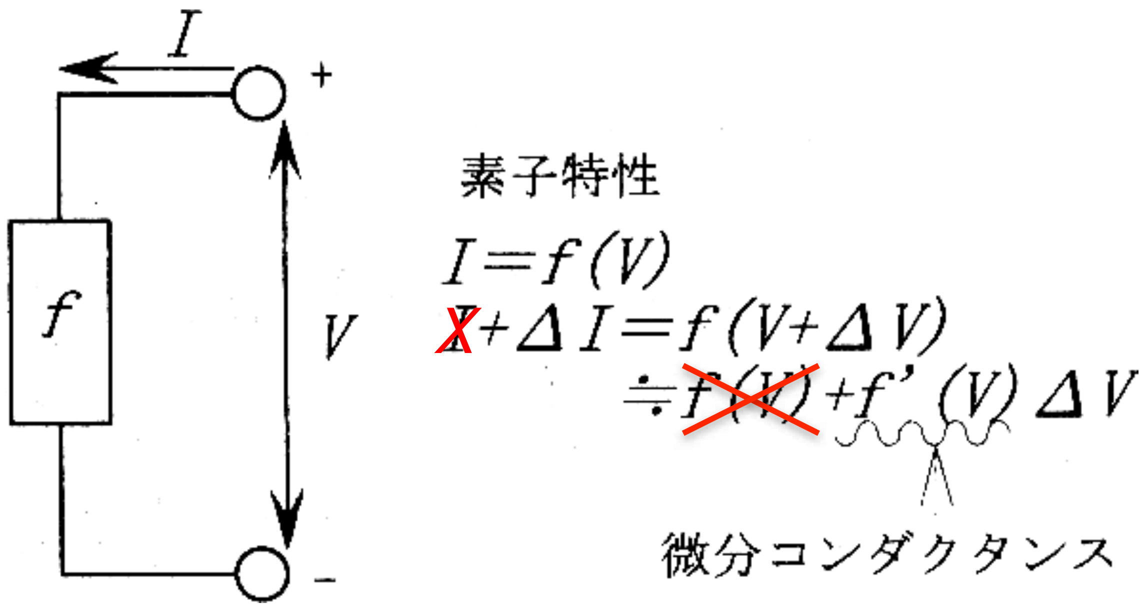


Equivalent circuit in small signal analysis.

Equivalent circuit for non-linear element

Many electronics elements has non-linear characteristic, so it is difficult to solve analytically.

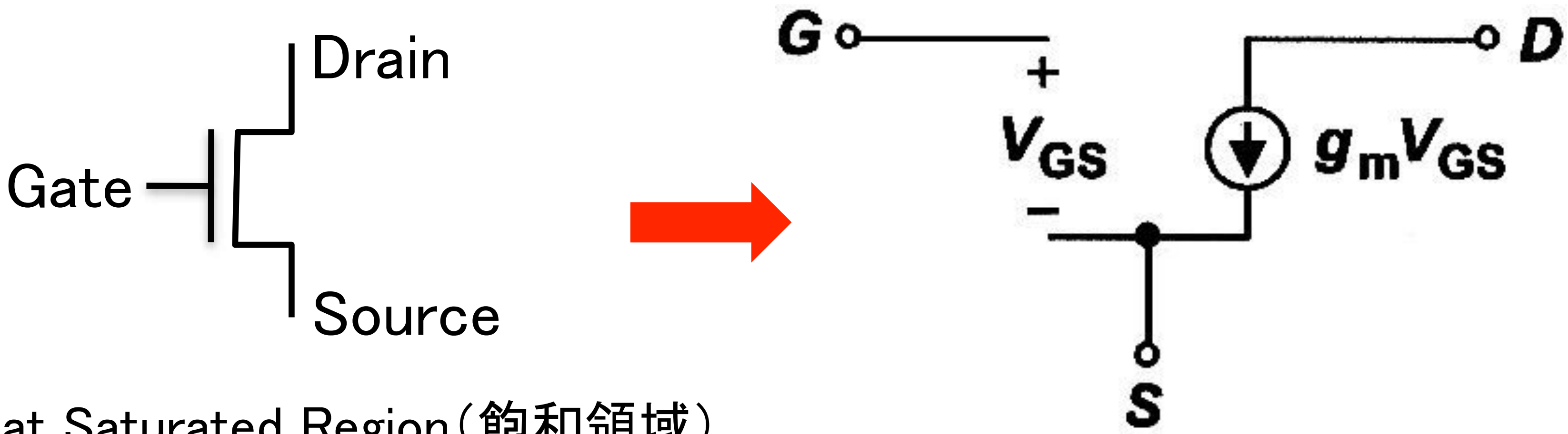
In most of case we would like to know response to small signal, they are replaced with linearized equivalent circuit.



How to make linear equivalent circuit

- Derive bias voltage from DC condition.
- Extract differential conductance at the bias voltage.
- Put voltage source to short, and current source to open.
- Make input signal as small input signal only.

Equivalent circuit of MOS Transistor



at Saturated Region（飽和領域）

$$I_{ds} = \beta \frac{\left(V_{gs} - V_{th}\right)^2}{2}$$

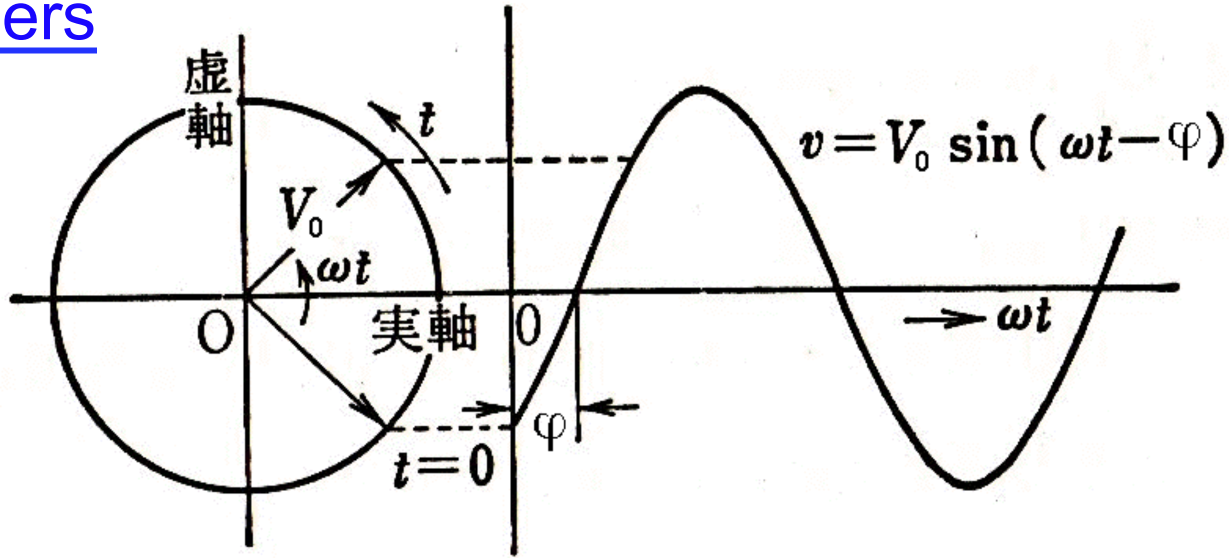
$$(V_{ds} > V_{gs} - V_{th})$$

$$g_m = \left.\frac{\partial I_{ds}}{\partial V_{gs}}\right|_{Saturated\,Region} = \beta\left(V_{gs} - V_{th}\right)$$

$$\partial I_{ds} = g_m \partial V_{gs} \Rightarrow I_{ds} = g_m V_{gs}$$

Make Gate current to 0, and Drain current to 'g_m x V_{GS}'.

Using Complex Numbers in AC Circuit Analysis



Use complex voltage V instead of sine wave v and make calculation

$$V = V_0 e^{i(\omega t - \varphi)} = V_0 \cos(\omega t - \varphi) + i V_0 \sin(\omega t - \varphi)$$

phasor表示

From the calculation result, actual voltage is obtained from the imaginary part.

In case of Current

$$I = I_0 e^{i(\omega t - \varphi)}$$

This will ease the calculation!

Using Complex Numbers in AC Circuit Analysis

By using complex number, differentiation and integration become multiplication and division.

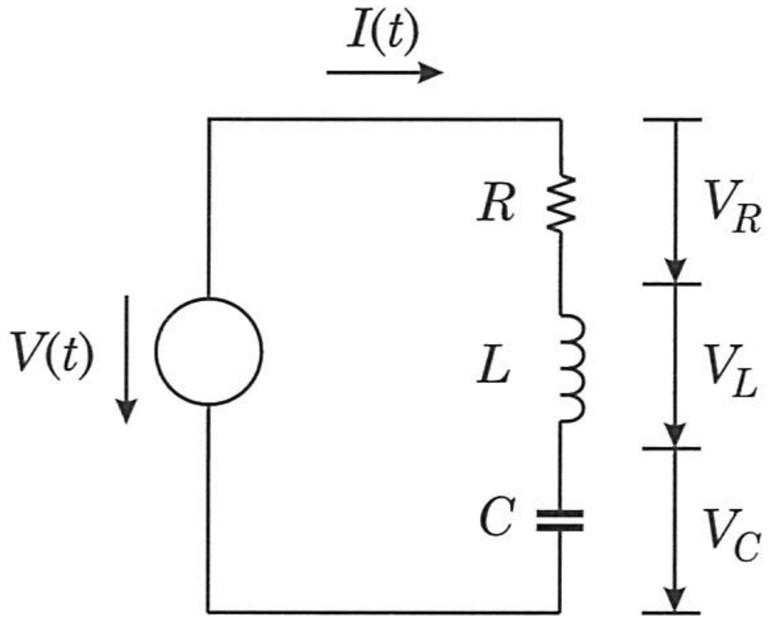
$$\frac{dI}{dt} = j\omega I, \qquad \frac{dV}{dt} = j\omega V$$

$$\int I\,dt = \frac{I}{j\omega}, \quad \int V\,dt = \frac{V}{j\omega}$$

In electronics circuit calculation, 'j' is used as imaginary unit since 'i' is confused with current.

交流回路の複素計算法

$$V(t) = V_R + V_L + V_C$$
$$= I(t)\cdot R + L\frac{dI(t)}{dt} + \frac{1}{C}\int I(t)\cdot dt$$



$$\begin{cases} \dfrac{d}{dt}V(t) = \dfrac{d}{dt}I(t)\cdot R + L\cdot\dfrac{d^2}{dt^2}I(t) + \dfrac{1}{C}I(t) \\ V(t) = V_0 e^{j\omega t} \\ I(t) = I_0 e^{j(\omega t+\varphi)} \end{cases}$$

$$j\omega V(t) = j\omega R\cdot I(t) - \omega^2 L\cdot I(t) + \frac{1}{C}I(t)$$

$$Z \equiv \frac{V(t)}{I(t)} = R + j\left(\omega L - \frac{1}{\omega C}\right)$$

複素インピーダンス

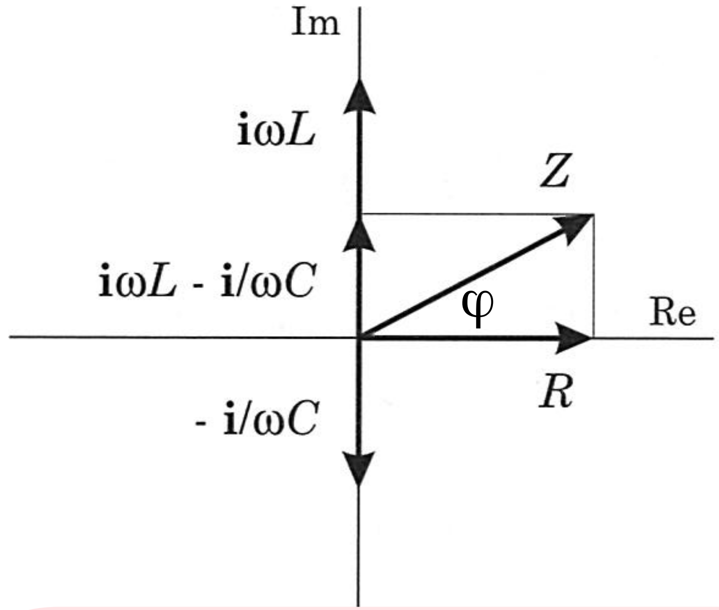
交流回路の複素計算法

$$|Z| = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}$$

$$\tan\varphi = \frac{\mathrm{Im}(Z)}{\mathrm{Re}(Z)} = \frac{\omega L - \frac{1}{\omega C}}{R}$$

従って、

$$I(t) = \frac{V_0}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}} \sin(\omega t - \varphi)$$



$$X = \omega L - \frac{1}{\omega C} \quad \text{--- Reactance}$$

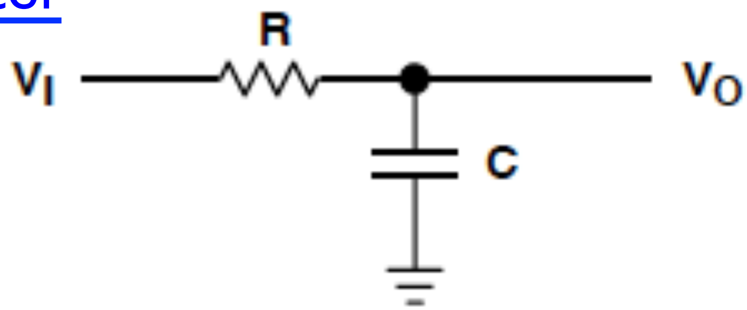
$$\omega L - \frac{1}{\omega C} = 0 \quad \Rightarrow \quad \omega_0 = \frac{1}{\sqrt{LC}}$$

$$\omega < \omega_0: \quad \omega L < \frac{1}{\omega C}, \varphi \to -90^\circ$$ Capacitive

$$\omega = \omega_0: \quad \varphi = 0^\circ$$ Resonance

$$\omega > \omega_0: \quad \omega L > \frac{1}{\omega C}, \varphi \to +90^\circ$$ Inductive

Frequency response of Low Pass Filter



$$\frac{V_o}{V_i} = \frac{1/j\omega C}{R + 1/j\omega C} = \frac{1}{1 + j\omega RC}$$

$$\Rightarrow \frac{1}{1 + j\omega\tau} \qquad (\tau = RC)$$

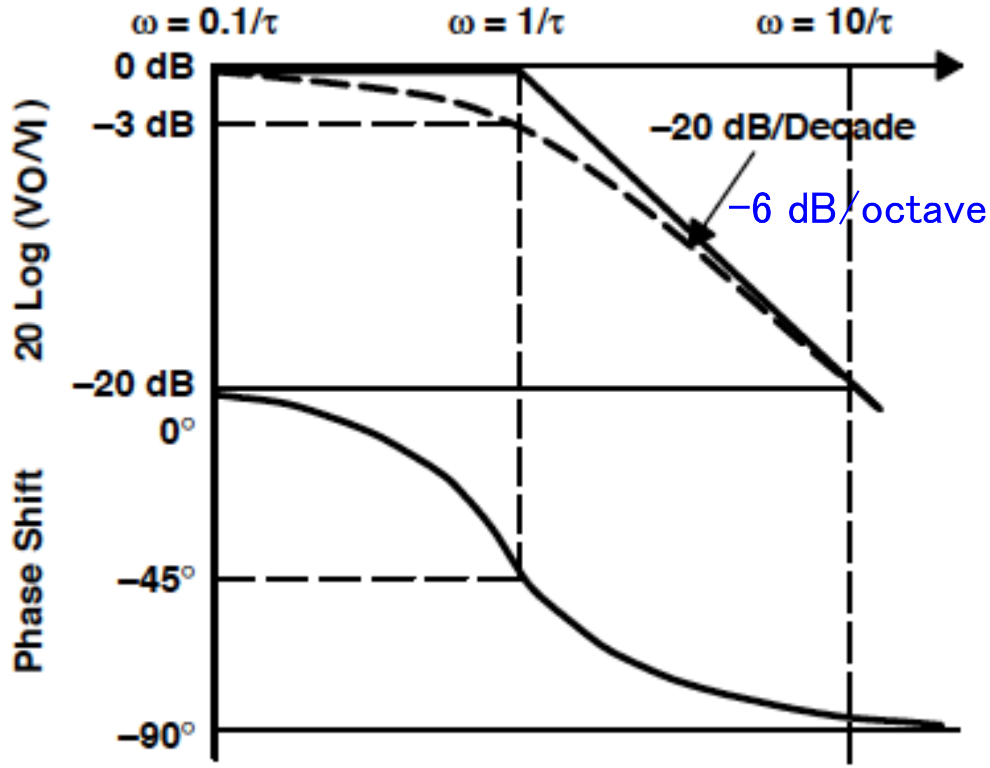
Gain G

$$G(i\omega) = \left|\frac{V_o}{V_i}\right| = \frac{1}{\sqrt{1 + (\omega\tau)^2}}$$

$$\Rightarrow \frac{1}{\omega\tau} \quad (\omega\tau >> 1)$$

Phase Shift ϕ

$$\phi = \tan^{-1}\left(\frac{real}{imaginary}\right) = -\tan^{-1}(\omega t)$$



Bode Plot

Decibel表示

bel (B) is logarithm to base 10 of the ratio of two power quantities.
decibel (dB) is ten times (deci) of bel.
The human perception of the intensity (sound, light, ...) is nearly linearly related to the logarithm of intensity, so the dB scale can be useful to describe perceptual levels.

$$dB = 10\log_{10}\frac{P_2}{P_1} = 20\log_{10}\frac{V_2}{V_1}$$

Gain G

$$G(j\omega) = \frac{1}{\sqrt{1+(\omega\tau)^2}} \rightarrow \frac{1}{\omega\tau}\ (\omega\tau >> 1)$$

$$20\log\frac{1/2\omega\tau}{1/\omega\tau} = 20\log\frac{1}{2} = -6\ \mathrm{dB/octave}$$

$$20\log\frac{1/10\omega\tau}{1/\omega\tau} = 20\log\frac{1}{10} = -20\ \mathrm{dB/decade}$$

$$\log_{10} 2 = 0.3010$$

参考：デシベルは本来2つの量の比を表す値だが、ある基準を用いて絶対値を表すことがある。様々な定義があり、混乱しやすいので注意。

例）

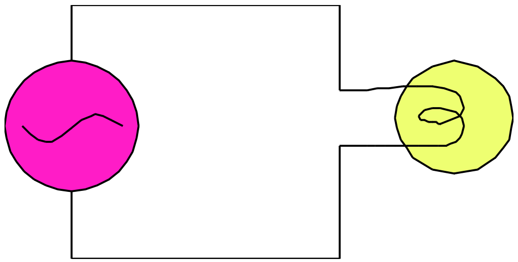
$$dBV = 20\log_{10}\frac{V}{1\ [\mathrm{Vrms}]}$$

$$dBm = 10\log_{10}\frac{P}{1\ [\mathrm{mWrms@600\Omega}]}$$

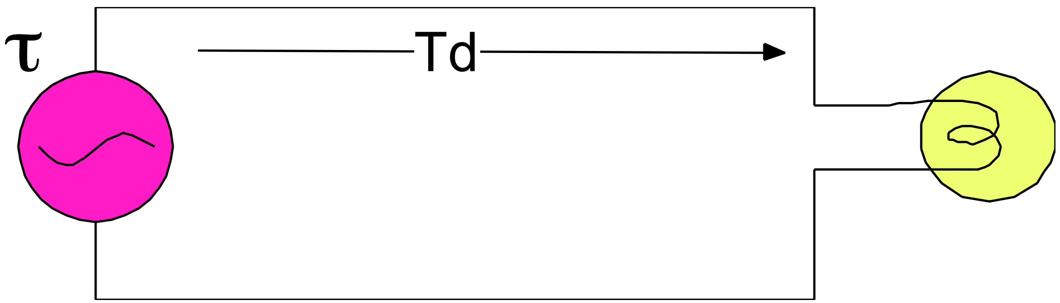
$$= 20\log_{10}\frac{V}{0.775\ [\mathrm{Vrms@600\Omega}]}$$

$$dB\mathrm{v} = 20\log_{10}\frac{V}{0.775\ [\mathrm{Vrms}]}$$

Signal propagation in transmission line



If the distance is short, the output changes with the input change.

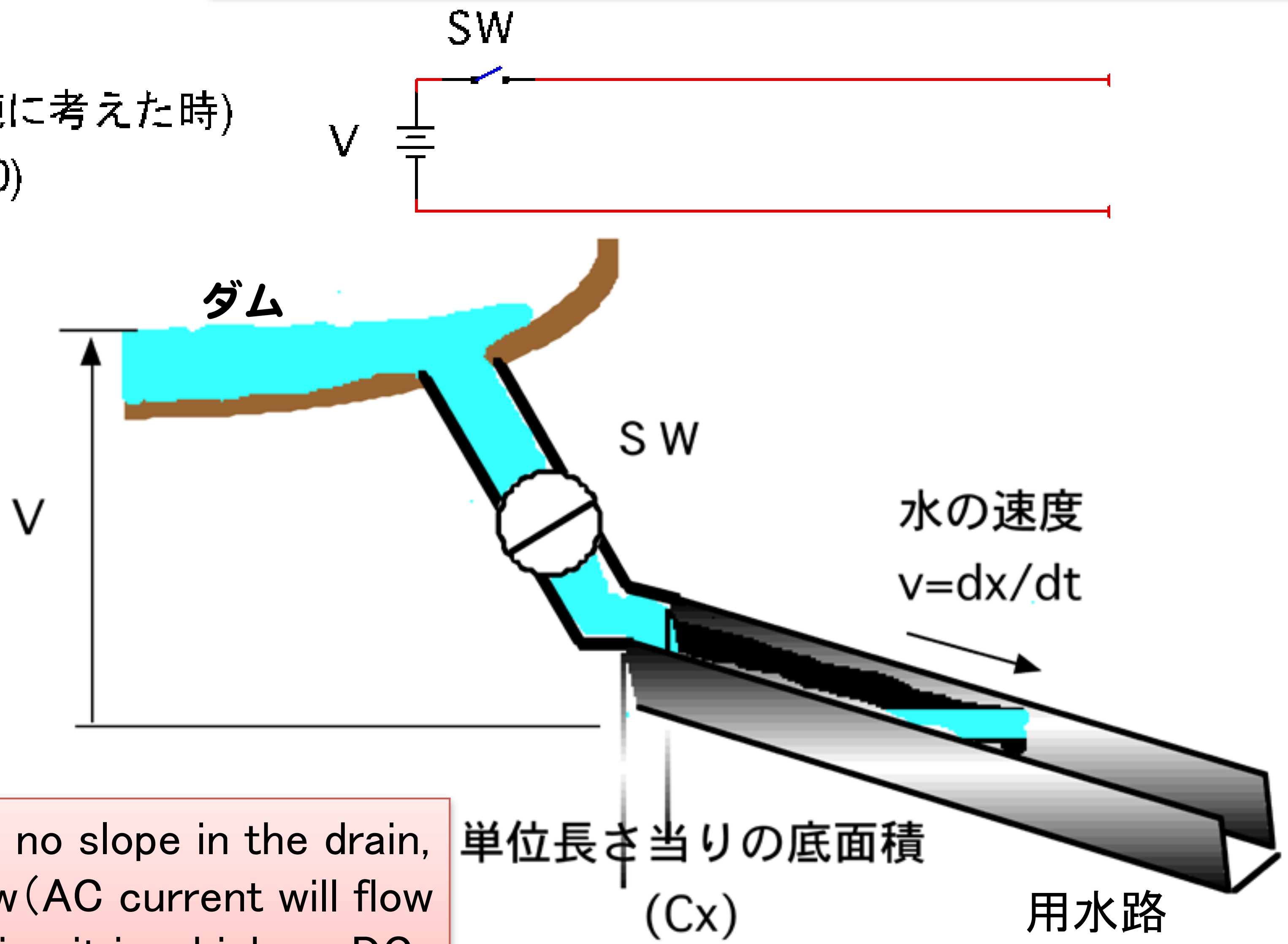


If the characteristic time of a input signal τ is shorter than the transmission time Td, the output signal is no more same as the input signal.

Transmission line

If you handle high speed signals, you have to think cable as a transmission line.

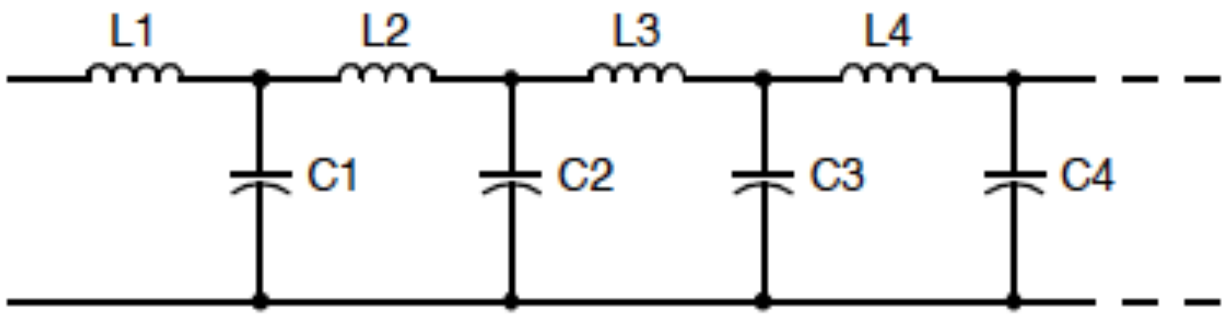
(最も単純に考えた時)
(R=0, L=0)



Even there is no slope in the drain, water will flow (AC current will flow even in the circuit in which no DC current flow.)

Transmission Line Theory

Figure 2-1. Lossless Transmission Line Model

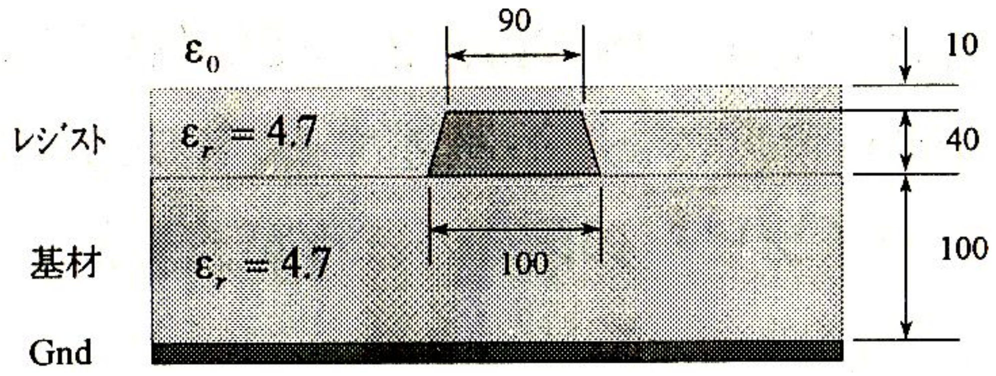


$$V_p = \frac{1}{\sqrt{LC}},$$ Transmission speed

$$Z_o = \sqrt{\frac{L}{C}},$$ Characteristic Impedance

$$T_d = \frac{1}{Vp} = \sqrt{LC}.$$ Signal propagation time

Ex.) Show transmission speed, Characteristic impedance, propagation time for 1 m in a printed circuit board of following value.



プリント基板断面 [μm]

R = 4.5 Ω/m
L = 360 nH/m
C = 120 pF/m

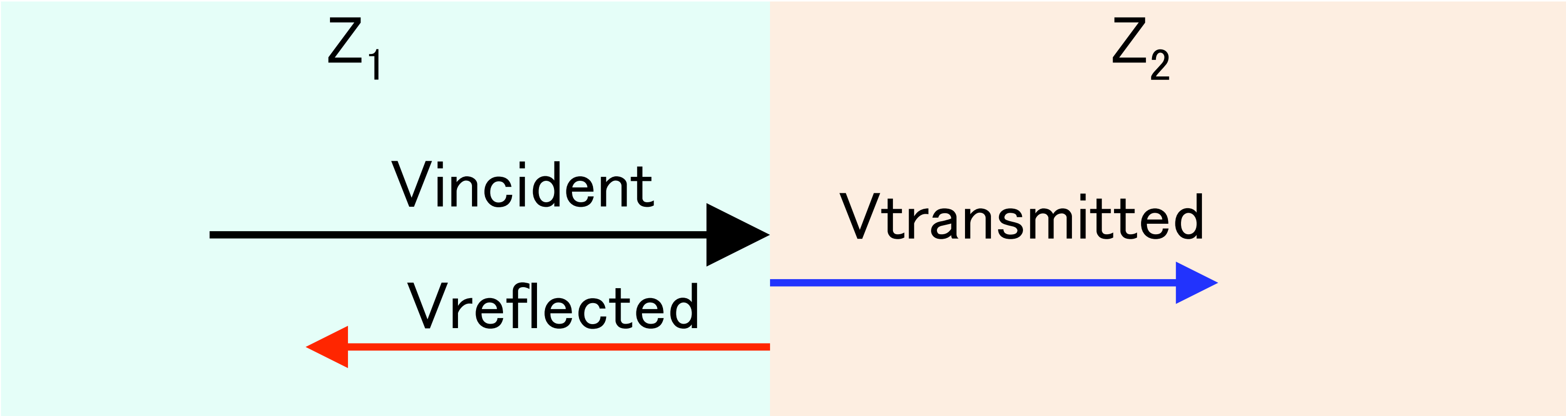
$$V_p = \frac{1}{\sqrt{360\times10^{-9}\cdot120\times10^{-12}}} = 1.5\times10^{8}\ [\mathrm{m/sec}]$$

光速の約半分

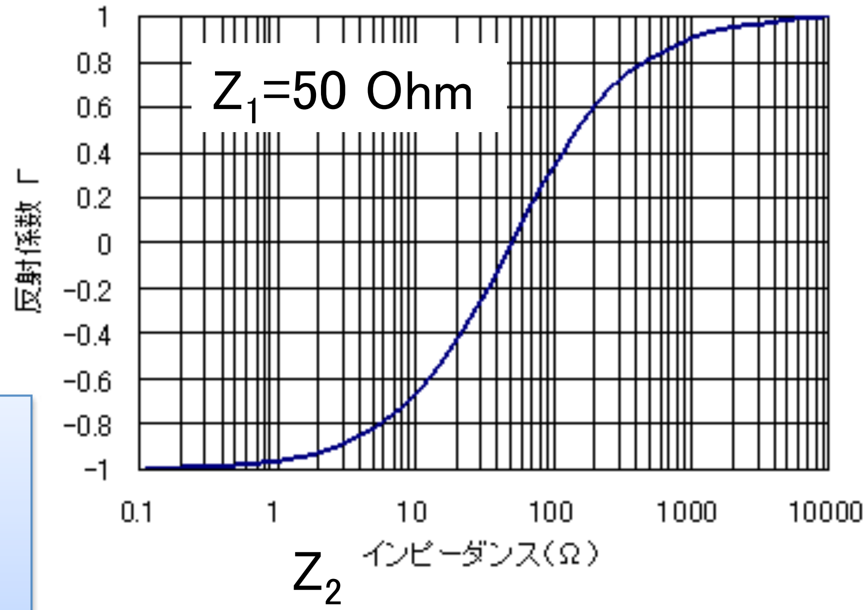
$$Z_0 = \sqrt{\frac{360\times10^{-9}}{120\times10^{-12}}} = 55\ [\Omega]$$

$$T_D = \sqrt{360\times10^{-9}\cdot120\times10^{-12}} = 6.6\ [\mathrm{nsec/m}]$$

Reflection Coefficient



$$\Gamma = \frac{V_{reflected}}{V_{incident}} = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

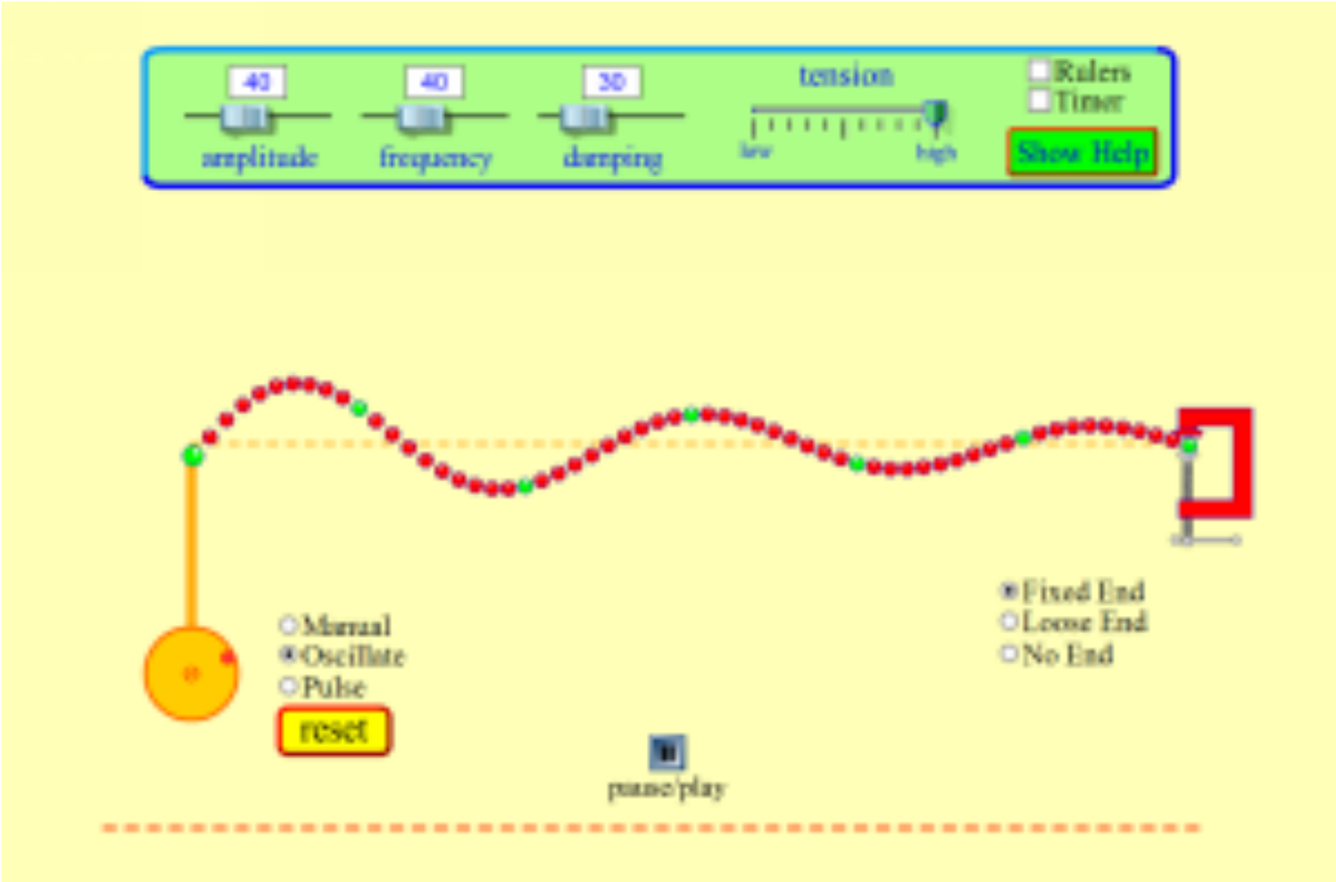


Z_2=Z_1　ならば　$\Gamma = 0$ (反射無し)

Z_2=∞(open)　ならば　$\Gamma = 1$

Z_2=0 (short)　ならば　$\Gamma = -1$

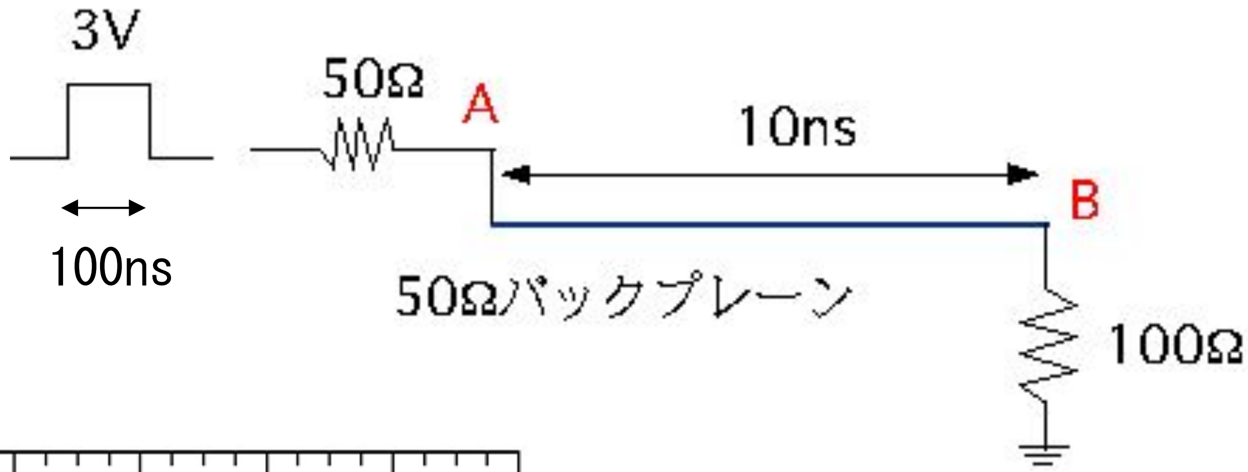
Wave on a String

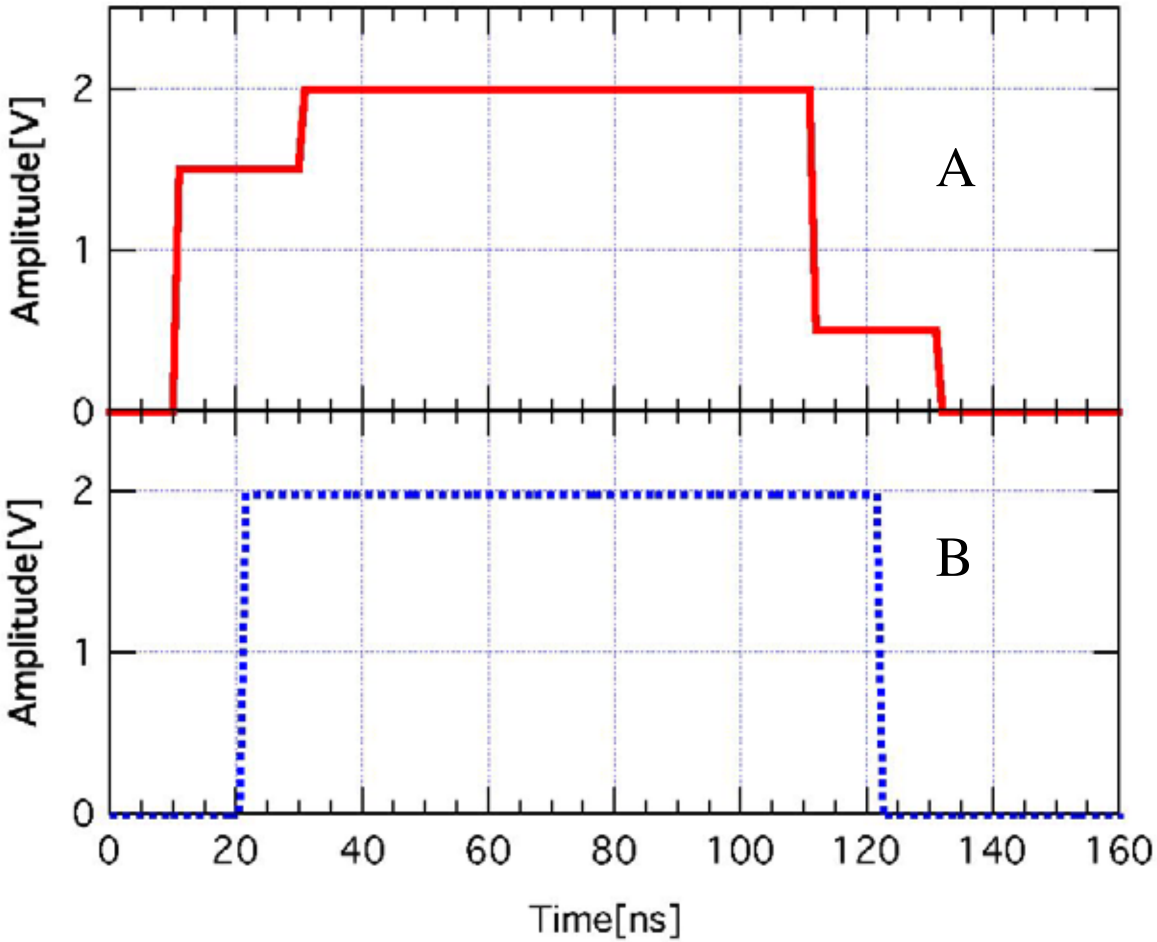


http://phet.colorado.edu/en/simulation/wave-on-a-string#software-requirements

例題1

t=10ns に幅100ns振幅3Vの信号を入力すると

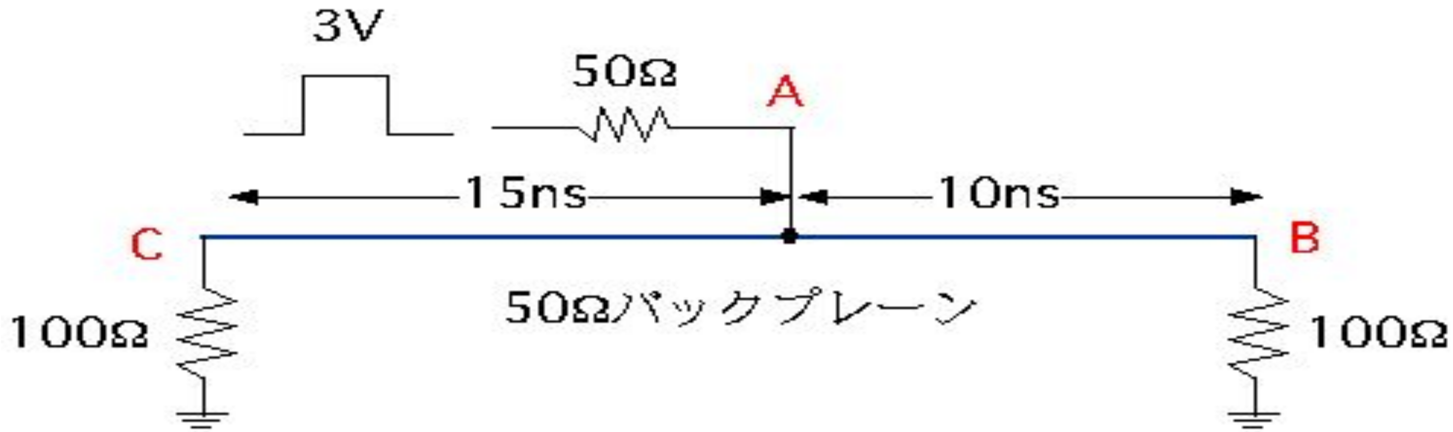


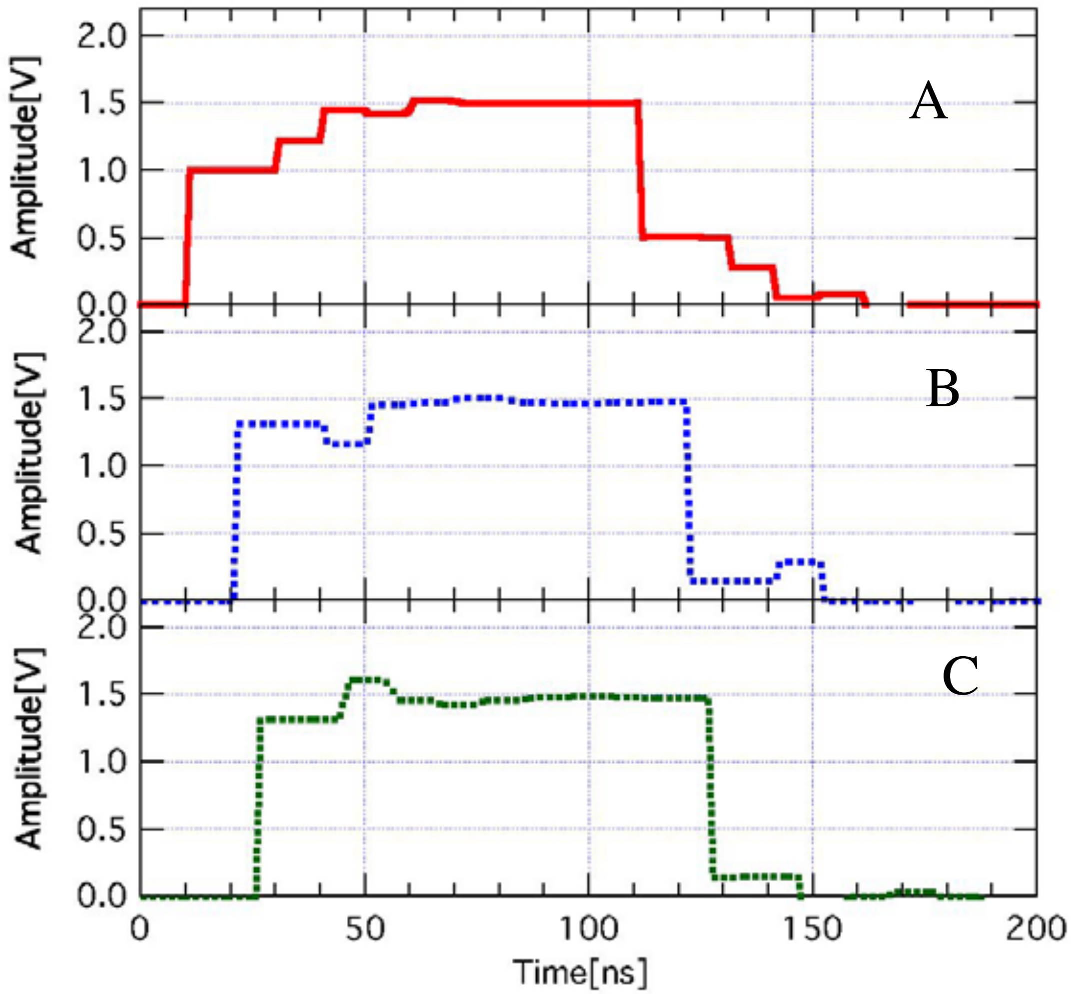


$$\rho_B = \frac{100-50}{100+50} = 0.33$$

$$\rho_A = \frac{50-50}{50+50} = 0$$

例題2



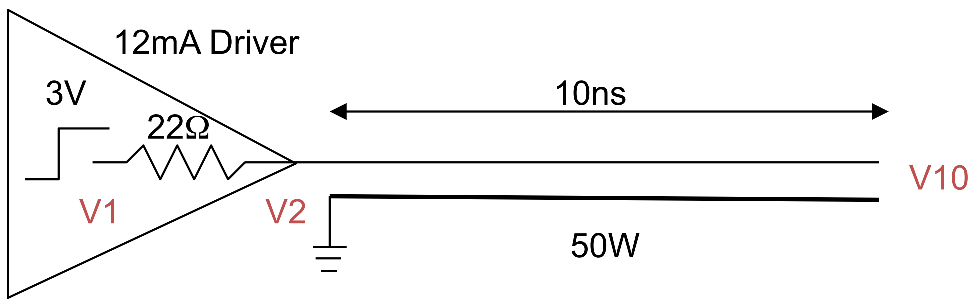


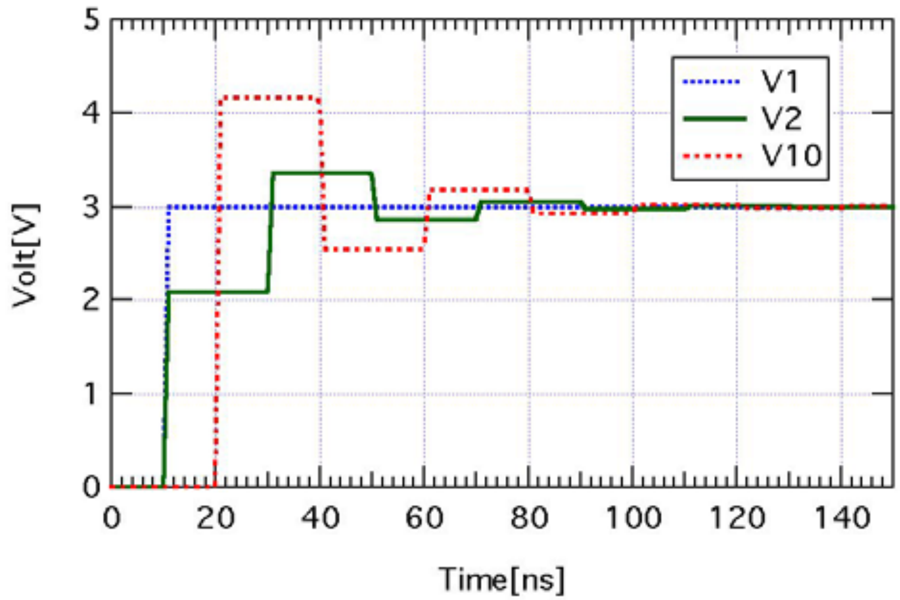
$$\rho_A = \frac{25-50}{25+50} = -0.33$$

$$\rho_B = \frac{100-50}{100+50} = 0.33$$

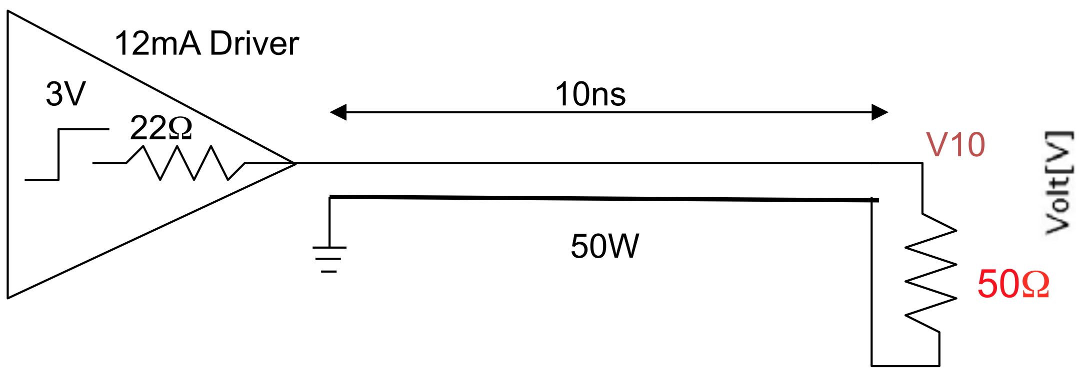
$$\rho_C = \frac{100-50}{100+50} = 0.33$$

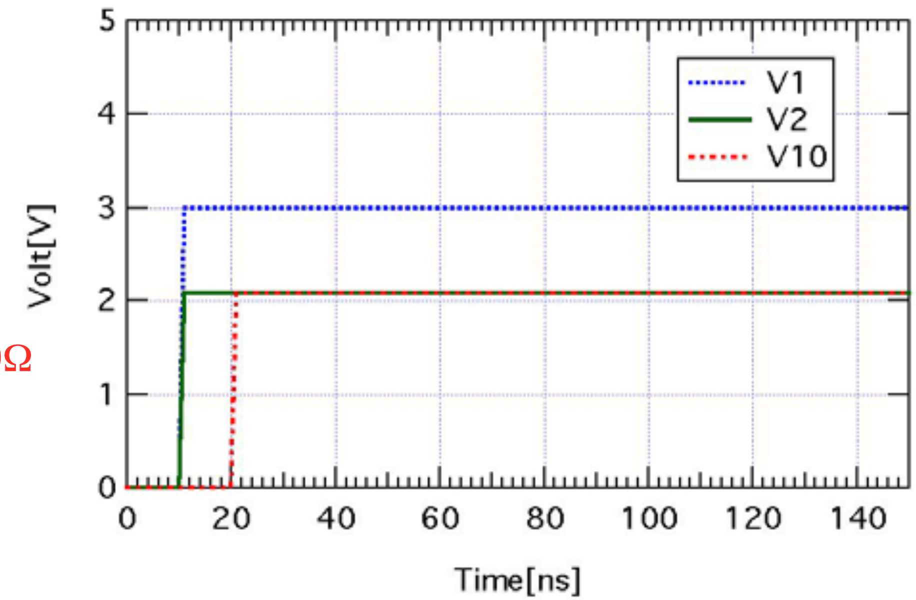
例題3





終端抵抗を付けると





波形はきれいになるが、
*電圧が下がる
*静的電流が流れる

cf. Internal resistance of a driver

Driving power of a driver is different depending on signal standard.

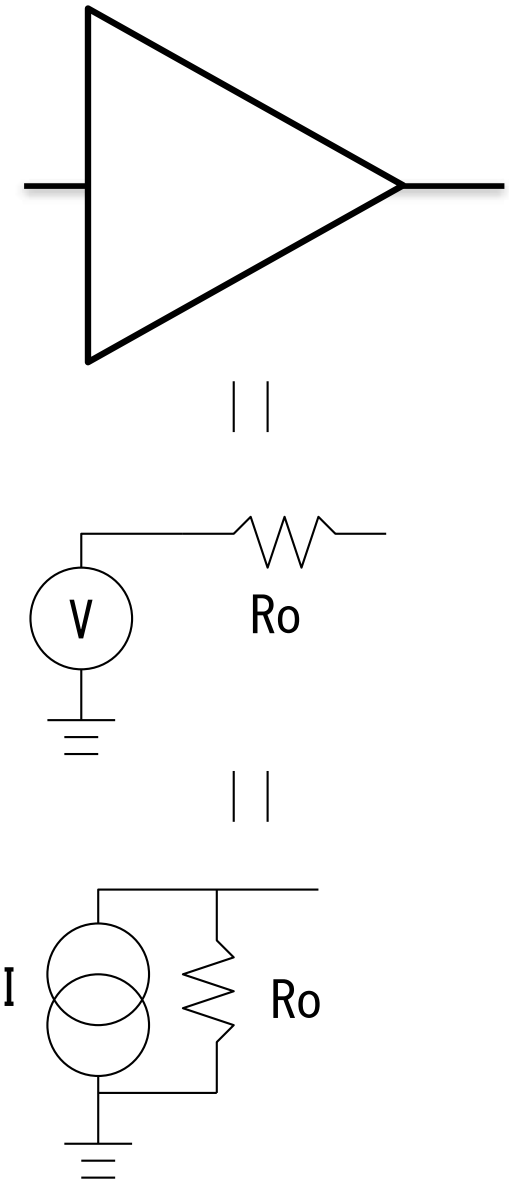
For example, in TTL logic, driving power is defined for low level output signal of 0.4V.

Normally, it has 1.5 times margin.

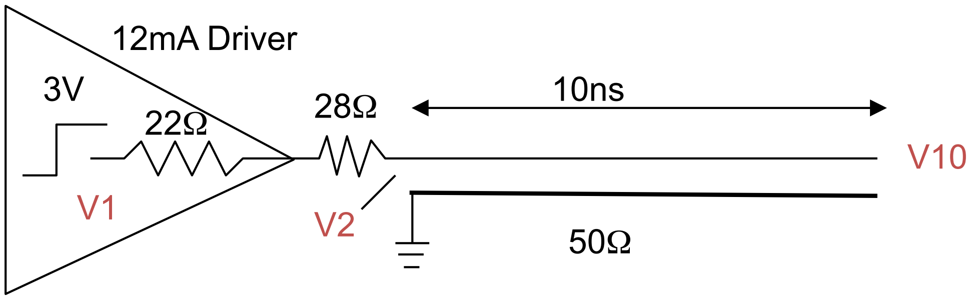
$$I_{OL} = \frac{V_{OL}}{R_O} \times \frac{1}{1.5}$$

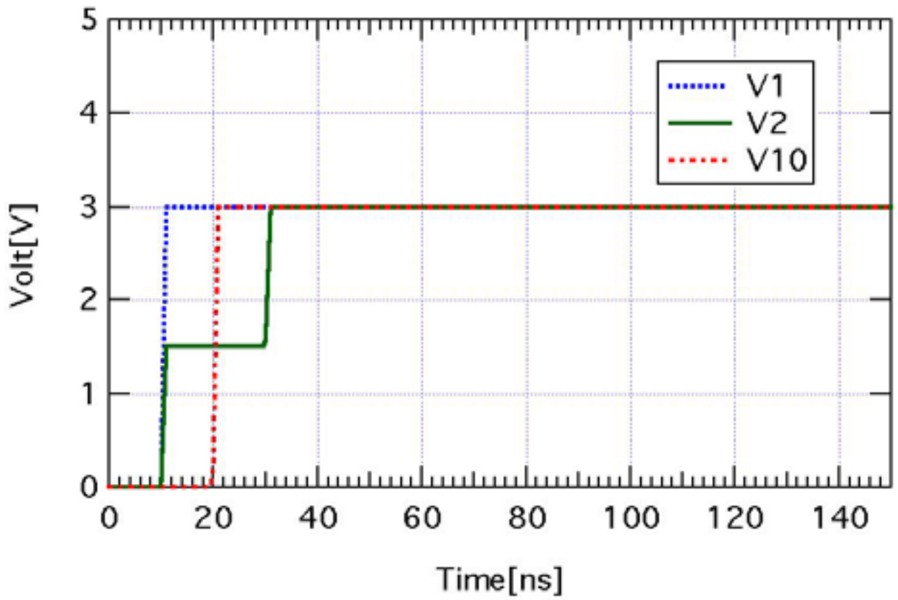
従って、規格値12mAの駆動能力を持つドライバーの内部抵抗は

$$R_O = \frac{V_{OL}}{I_{OL} \times 1.5} = \frac{0.4}{12 \times 1.5} = 22\ \Omega$$



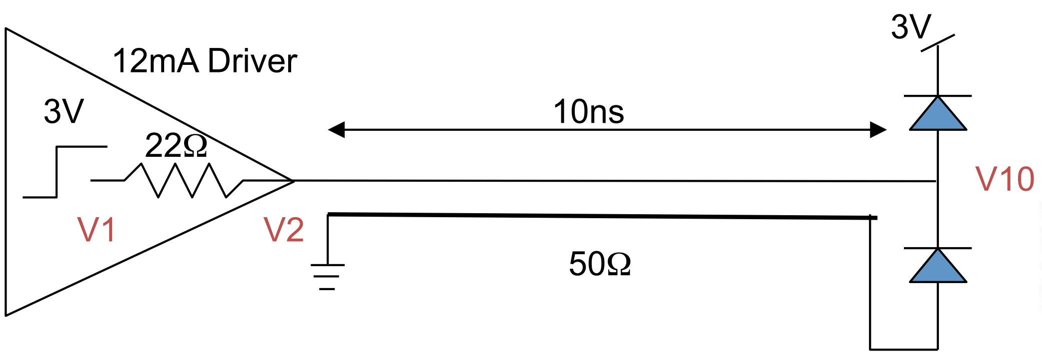
近端で整合を取る

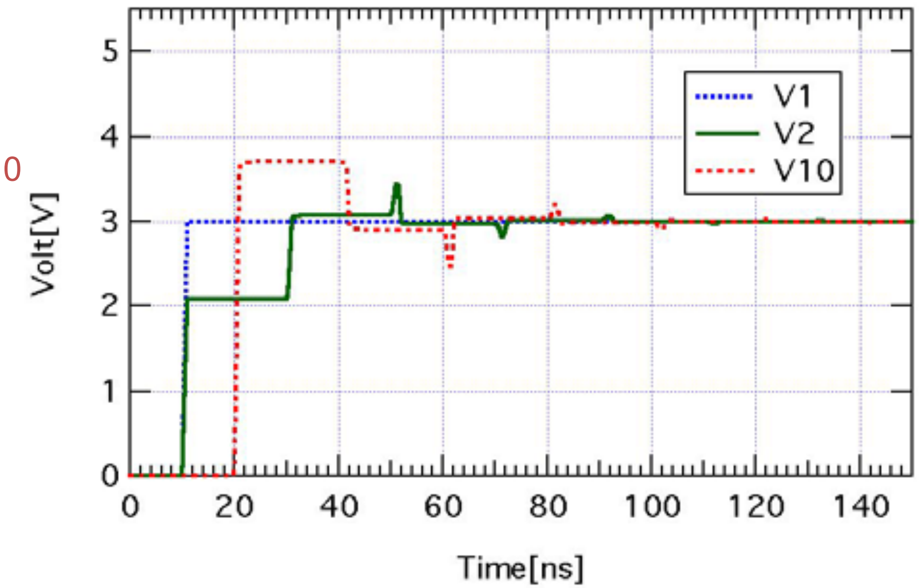




遠端の波形はきれい
静的電流も流れない
近端の波形は段が出来る

ダイオード終端

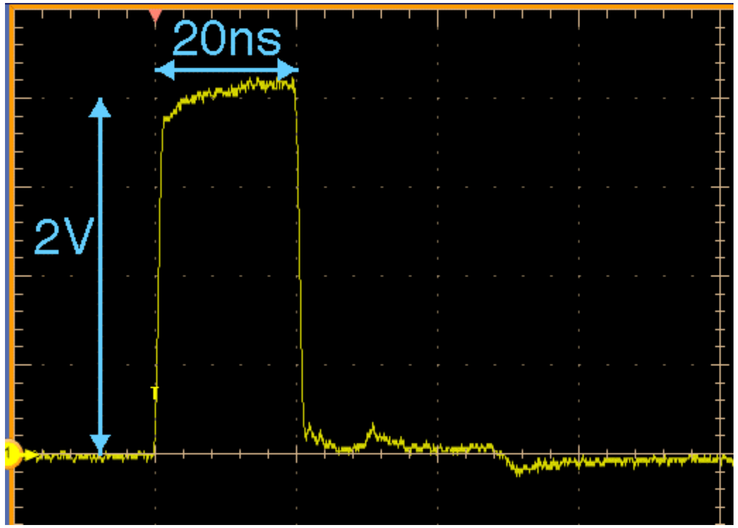


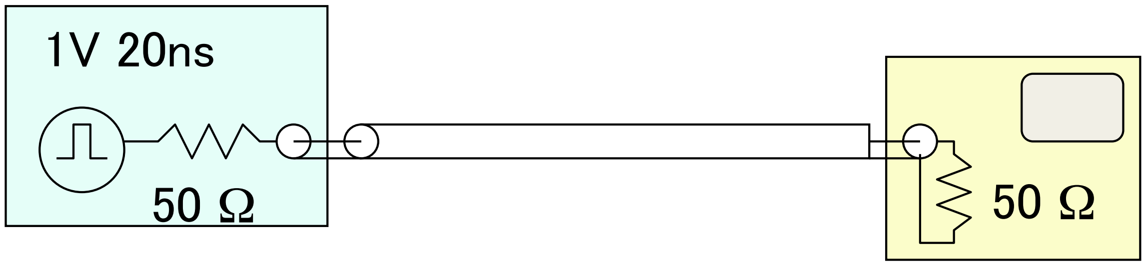


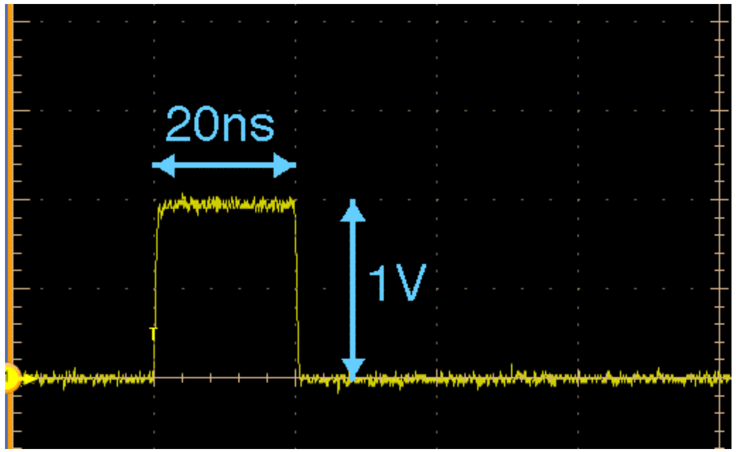
静的電流が流れない
グリッチが少し出る

Reflection experiment

1Vに設定したのに…

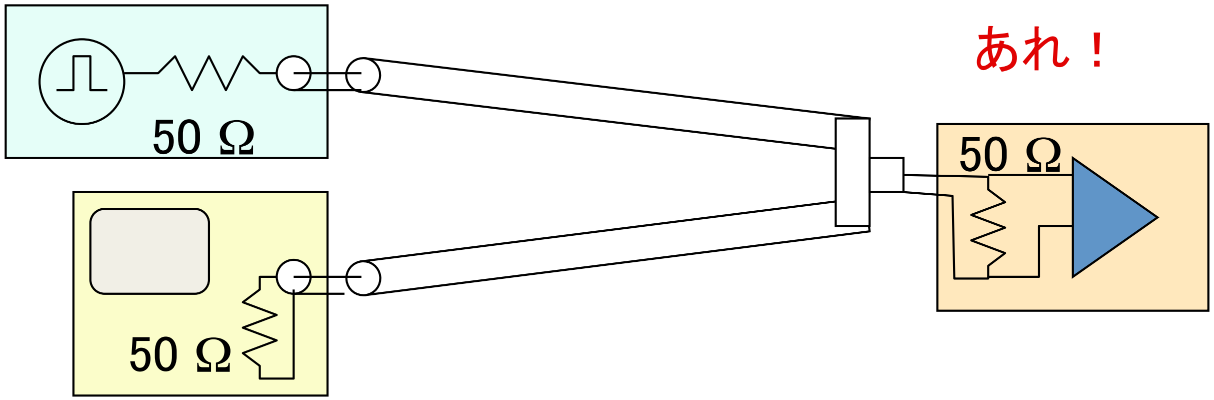




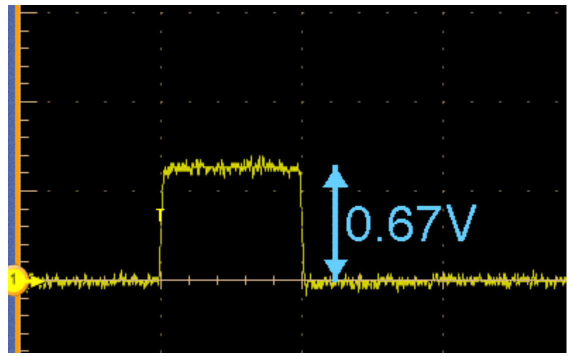


こうすると正しい波形が

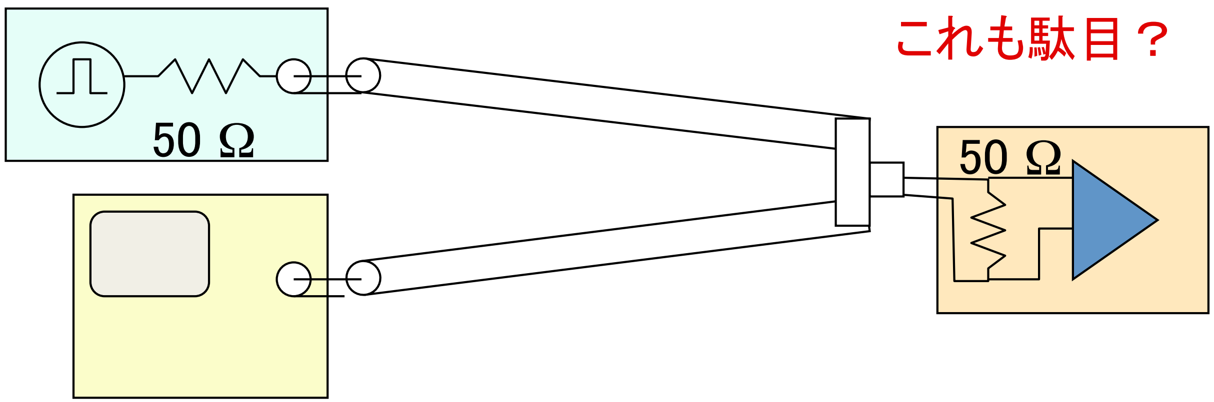
さあ、実際の測定をしよう！

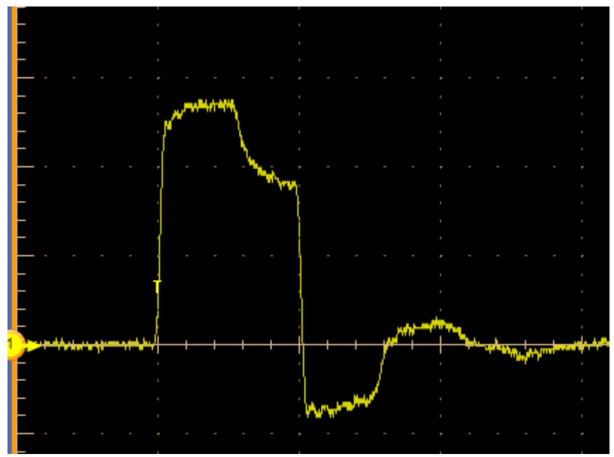


あれ！

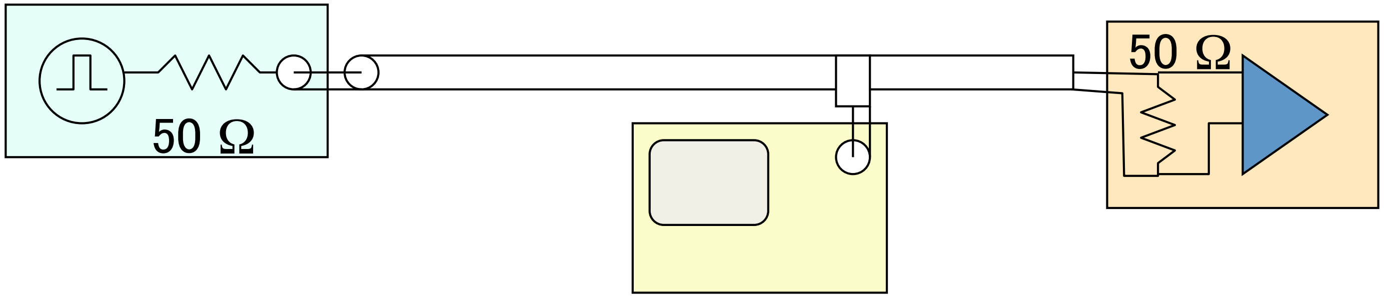


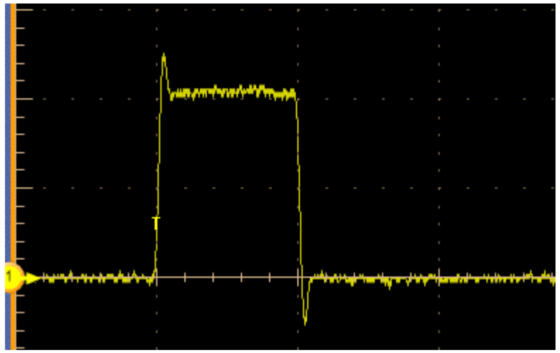
これも駄目？



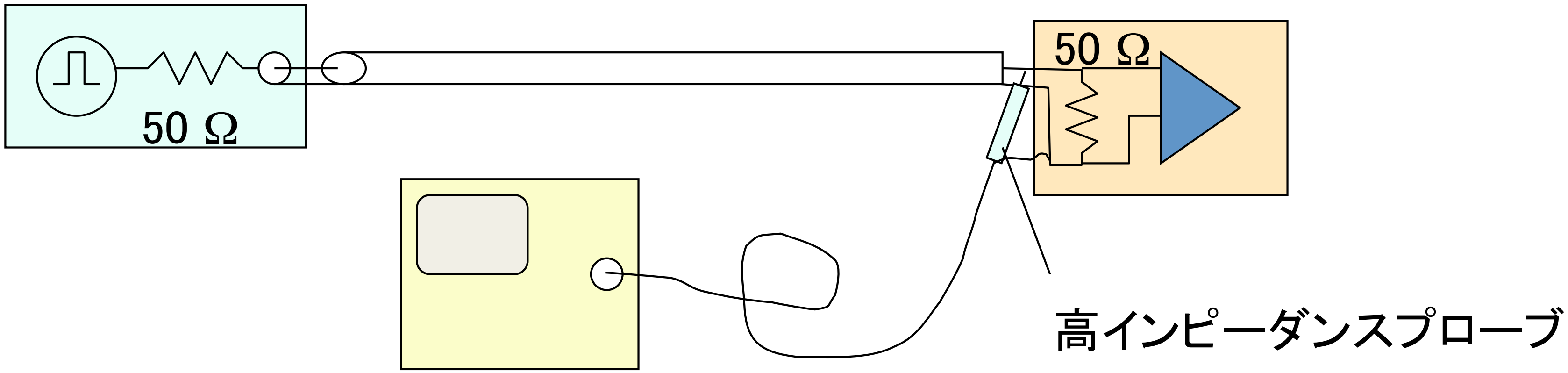


こういう時はオシロを高インピーダンスにして途中に入れるか





高インピーダンスプローブを使う



Oscilloscope probe

入力抵抗 ~10 MΩ
入力容量 ~10 pF
帯域 ~300MHz

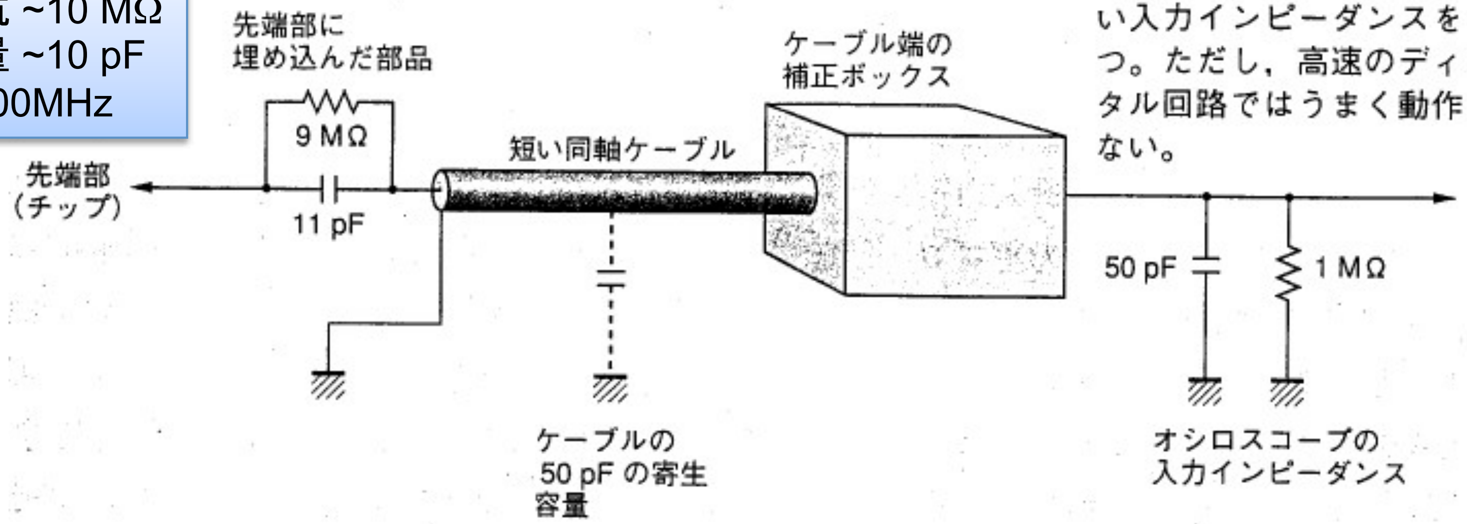


図1　容量入力型（受動型）プローブ　もともと真空管機器で使用するために開発された。直流の場合は高い入力インピーダンスをもつ。ただし，高速のディジタル回路ではうまく動作しない。

入力抵抗 ~1 MΩ
入力容量 ~1 pF
帯域　~2GHz

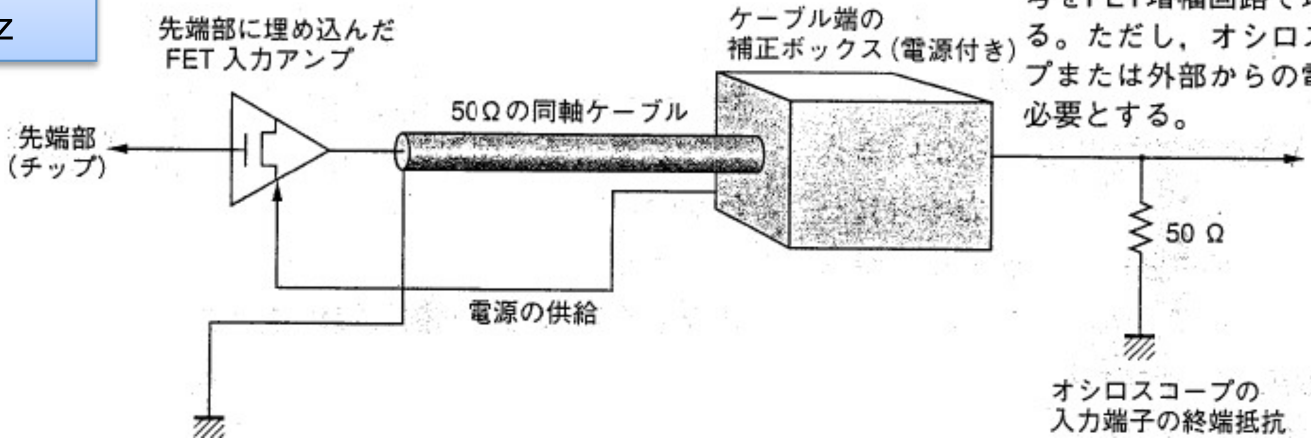
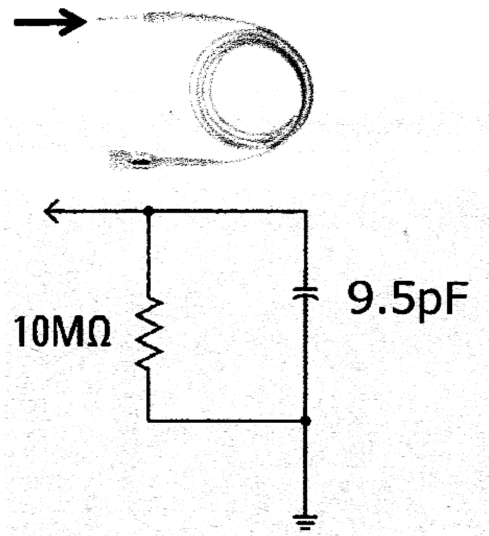
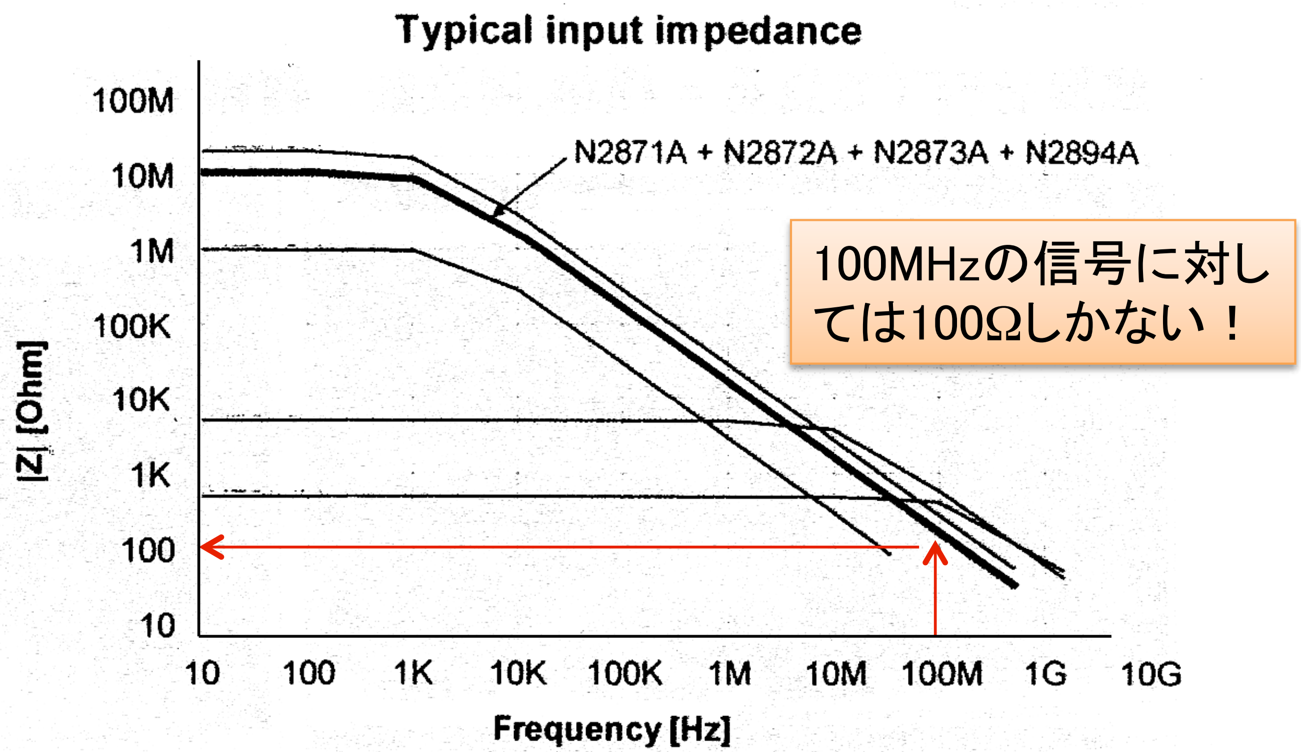


図2　FET入力型プローブ　性能向上のために，入力信号をFET増幅回路で増幅する。ただし，オシロスコープまたは外部からの電源を必要とする。

プローブのインピーダンス





容量性負荷の存在、入力容量による入力Z低下や回路動作タイミングへの影響、DC負荷などの影響を理解して利用する

出典：Typical Input Impedance for Each Probe Model, Figure 9. Typical Input Impedance
N2870A-Series and N2894A Passive Probes User's Guide, p/n N2876-97001

入力抵抗 ~1 kΩ
入力容量 ~2 pF
帯域 ~1GHz

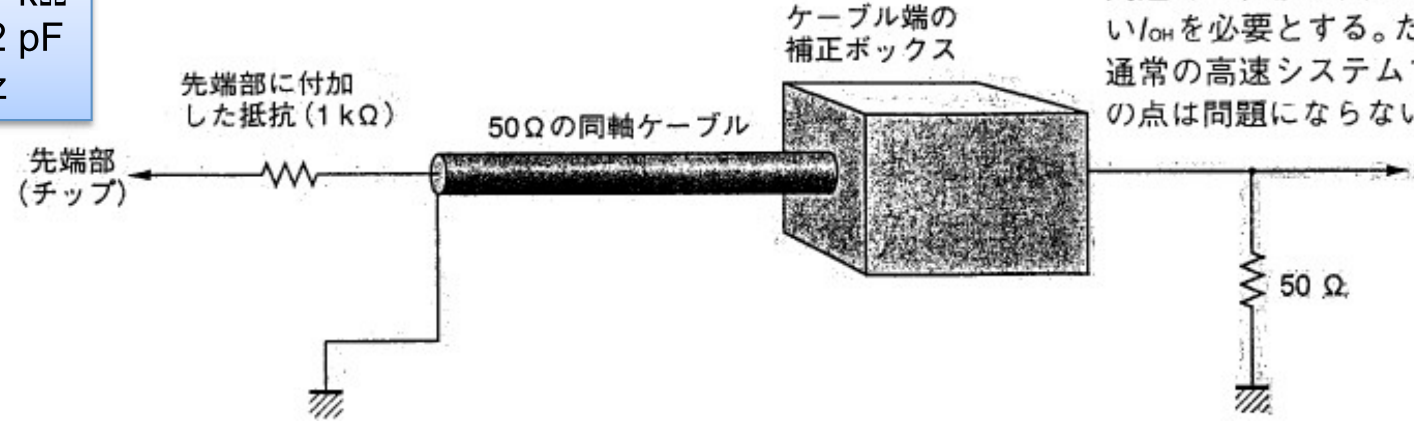
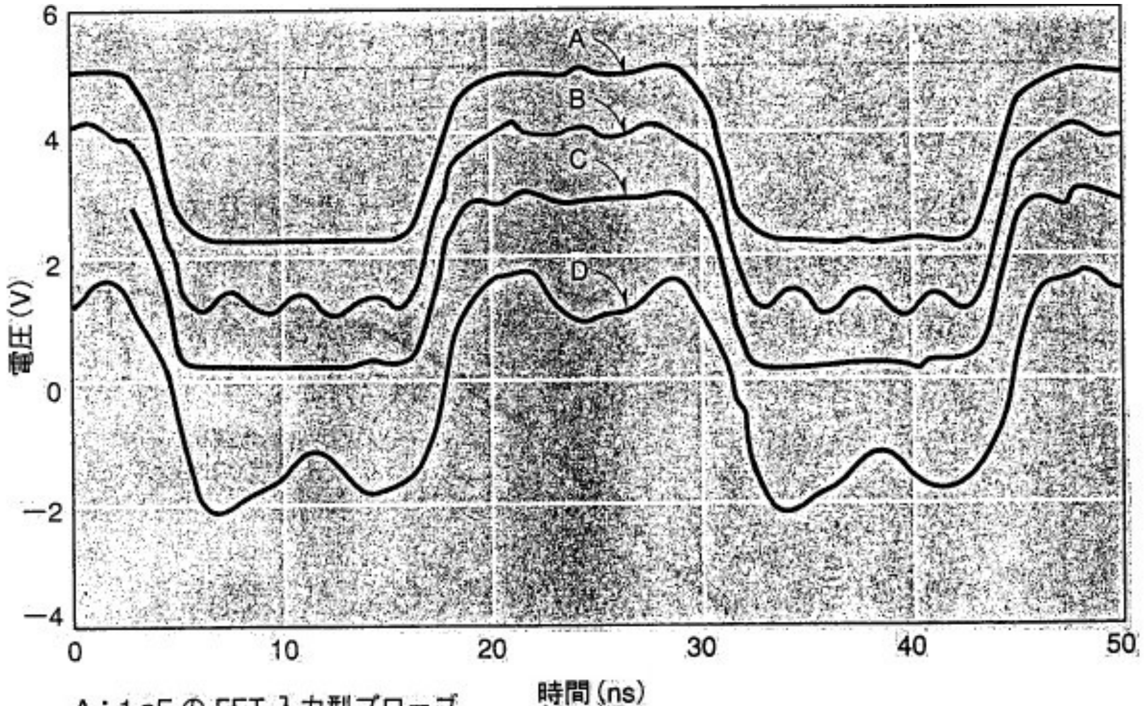


図3　抵抗入力型プローブ
高速でも性能は良いが，高いI_{OH}を必要とする。ただし，通常の高速システムではこの点は問題にならない。



A：1 pF の FET 入力型プローブ
B：1 pF の FET 入力型プローブ（6インチの接地線付き）
C：1 kΩ の抵抗入力型プローブ（6インチの接地線付き）
D：8 pF の容量入力型プローブ（6インチの接地線付き）

図5　37MHzのクロック信号を測定する　　接地線を利用しない場合は三つのプローブで同じ結果となった（A）。6インチの接地線を利用すると，リップルは抵抗入力型プローブで最も小さくなった。